AIP Publishing **Physics of Plasmas**

Features in Plasma Physics Webinar

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Vacuum arcs:
Understanding their physics from a viewpoint of unipolar arcs

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Some of this webinar is based on a recent *Featured Article* in PoP

Physics of Plasmas **ARTICLE** pubs.aip.org/aip/pop

Mechanism and current balance of unipolar arcs and implications for vacuum arcs

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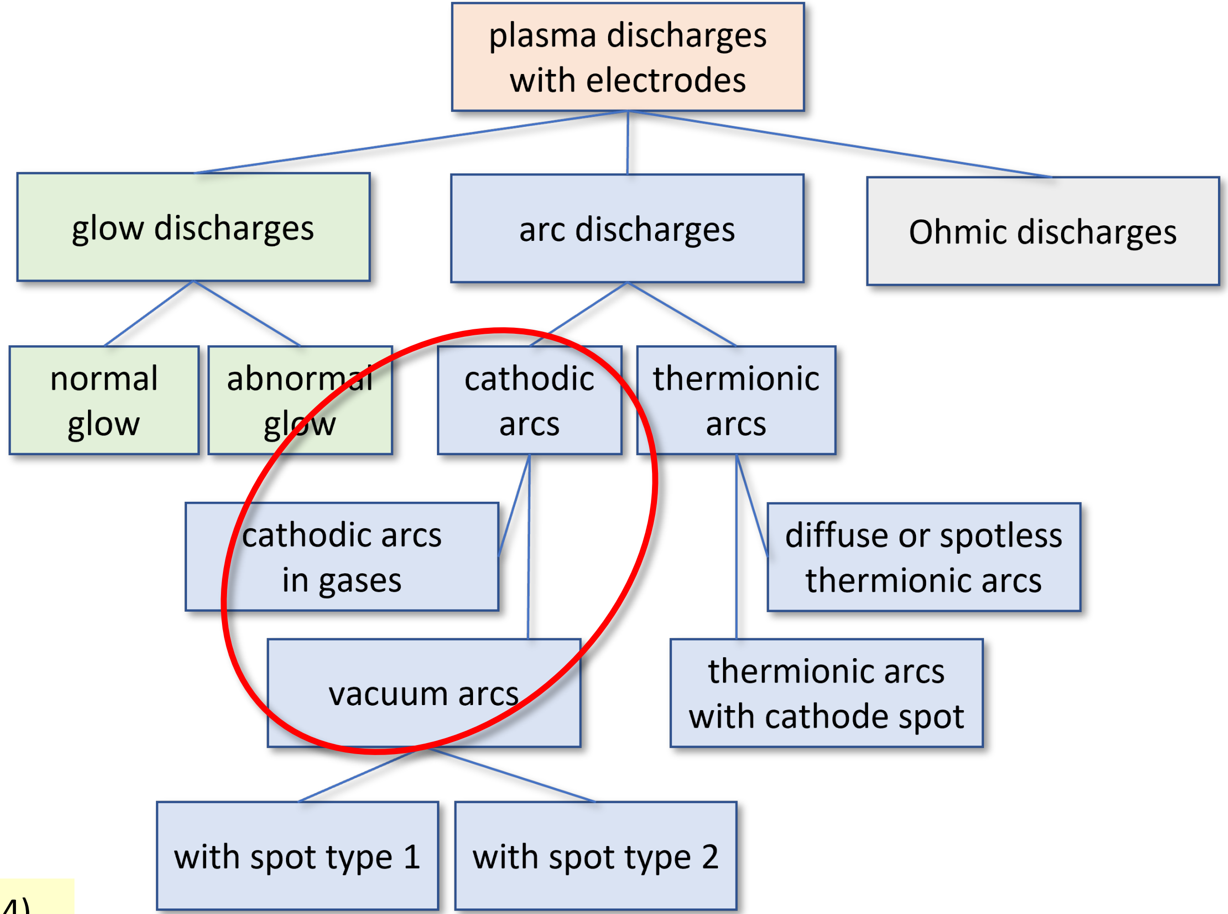
Terminology of *vacuum arcs* versus cathodic arcs

- **Vacuum arcs** = (cold cathode) arcs *in vacuum*, plasma material comes from cathode
- **Cathodic arcs** = (cold cathode) arcs, most plasma material comes from cathode

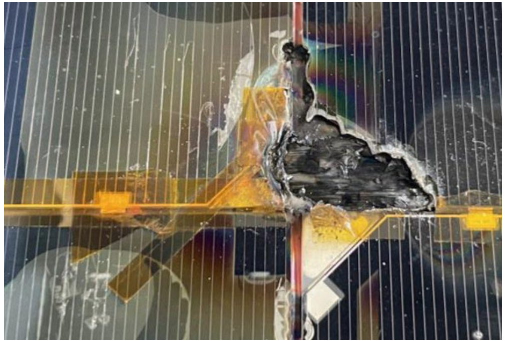
The terms are sometimes interchangeably used.



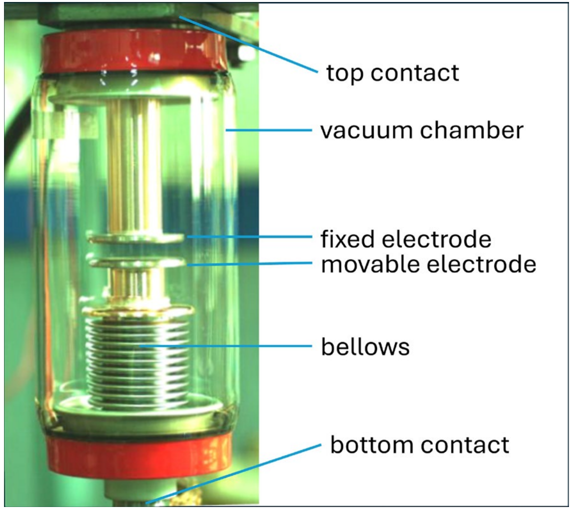
A. Anders, Appl. Phys. Rev. 11, 031310 (2024).

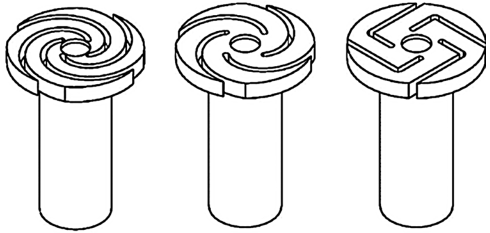
Vacuum arcs

ion beam space charge neutralization

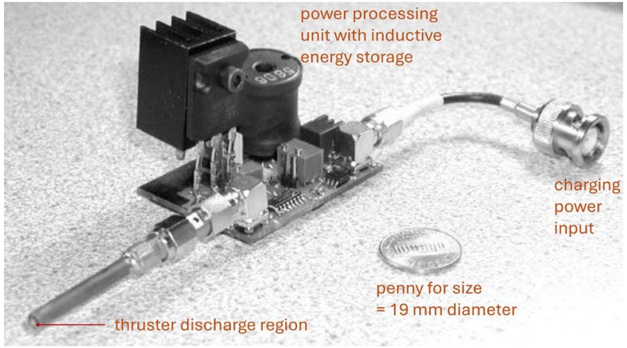


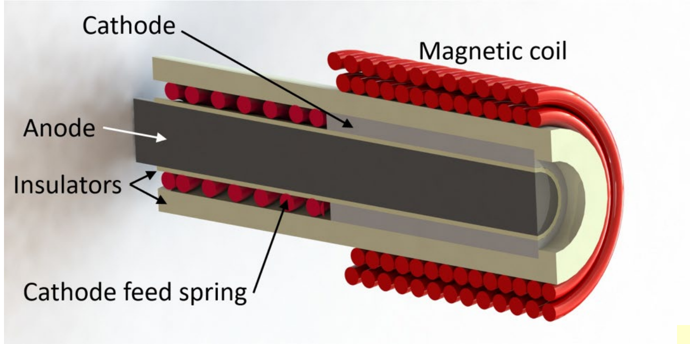
unwanted arcing on solar panels in space





vacuum arc switches



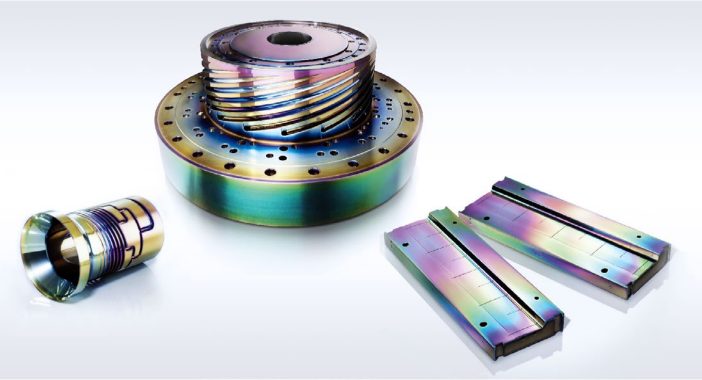


pulsed vacuum arc thrusters

for references see A. Anders, Cathodic Arcs, Springer, NY, 2026

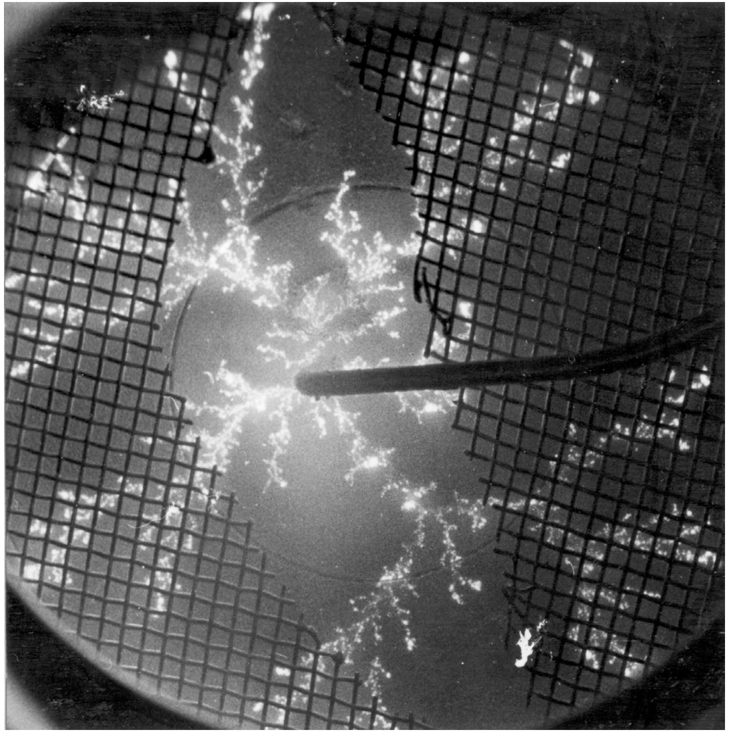
Cathodic arcs in coatings

nitrides, oxides, ta-C, multilayers, nanocomposites, ….

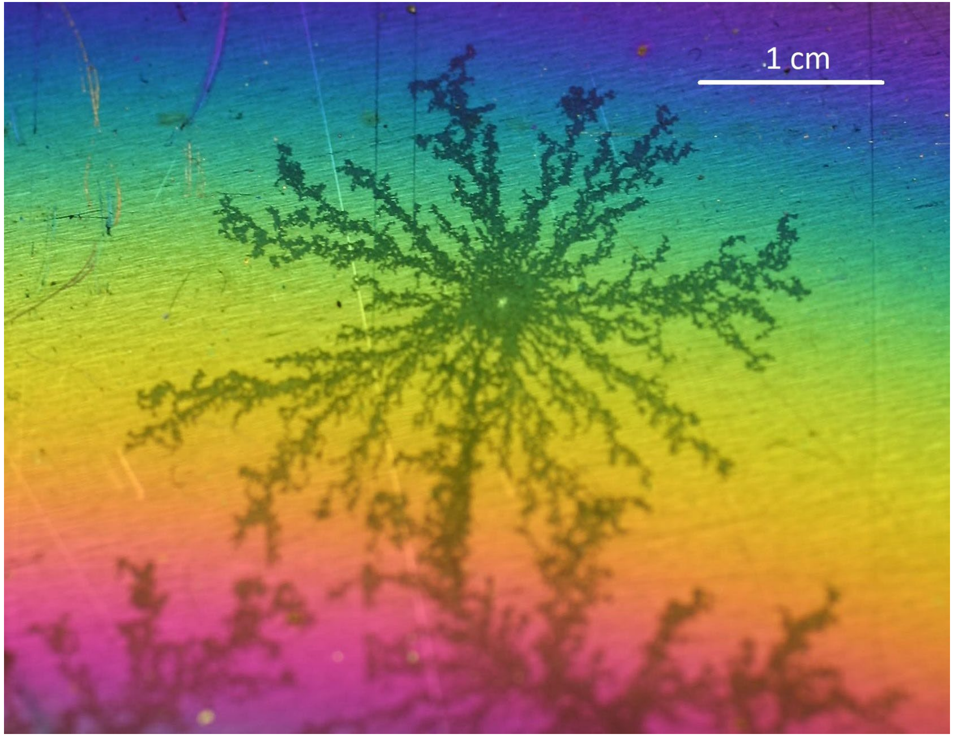


images courtesy of Oerlikon, Avalux

Unipolar versus vacuum arcs



vacuum arc
between cathode and anode

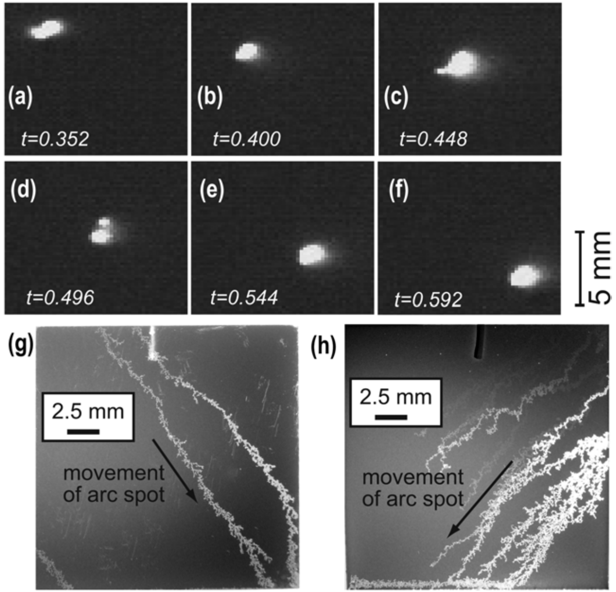


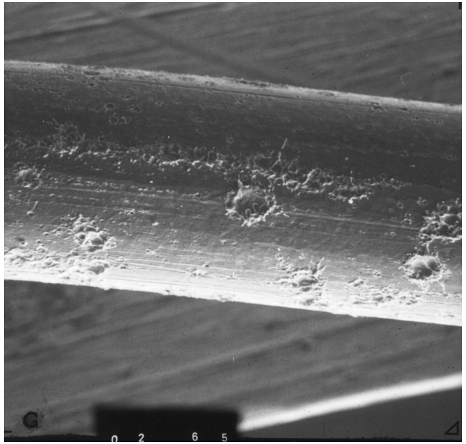
unipolar arc on a floating metal

A. Anders, Phys. Plasmas 33, 063505 (2026).

Unipolar arcs

- observation of cathode spots in the absence of an obvious anode
- on plasma-facing components (PFC) of fusion devices
- on very high-power RF structures (like RF cavities)

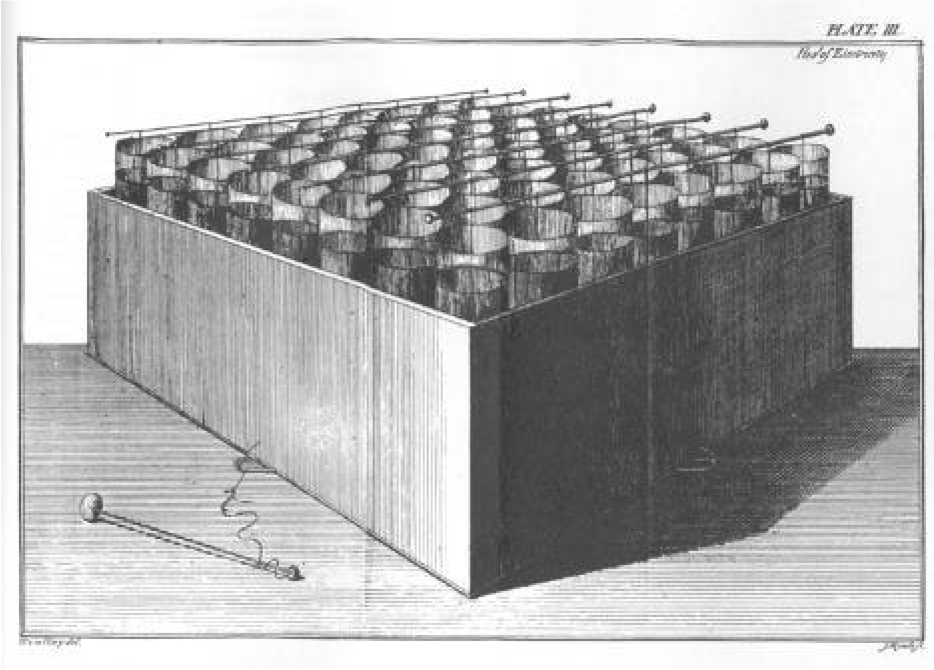




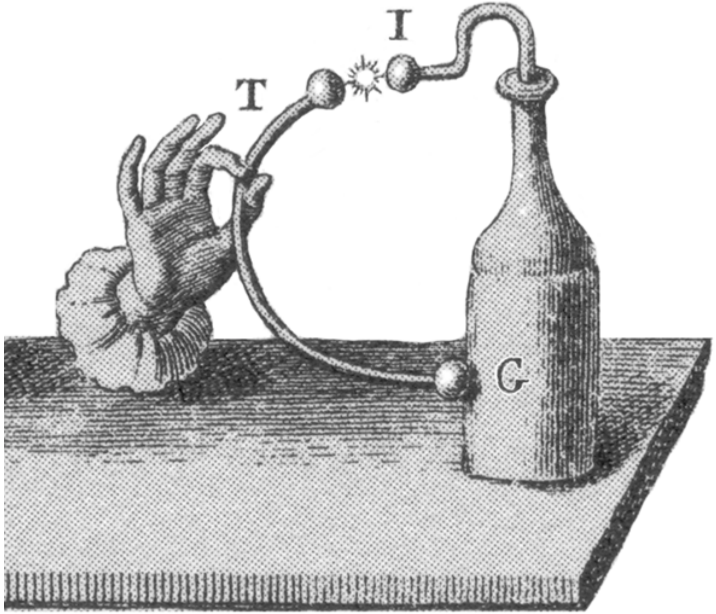
unipolar arcs are the unicorns among arcs: difficult to catch, but they do exist!

K. Jakubka and B. Jüttner, J. Nucl. Mat. 102, 259 (1981).
S. Kajita, et al., Nucl. Fusion 49, 032002 (2009).

From Charge to Discharge!



Battery of Leyden Jars (capacitors), ca. 1760

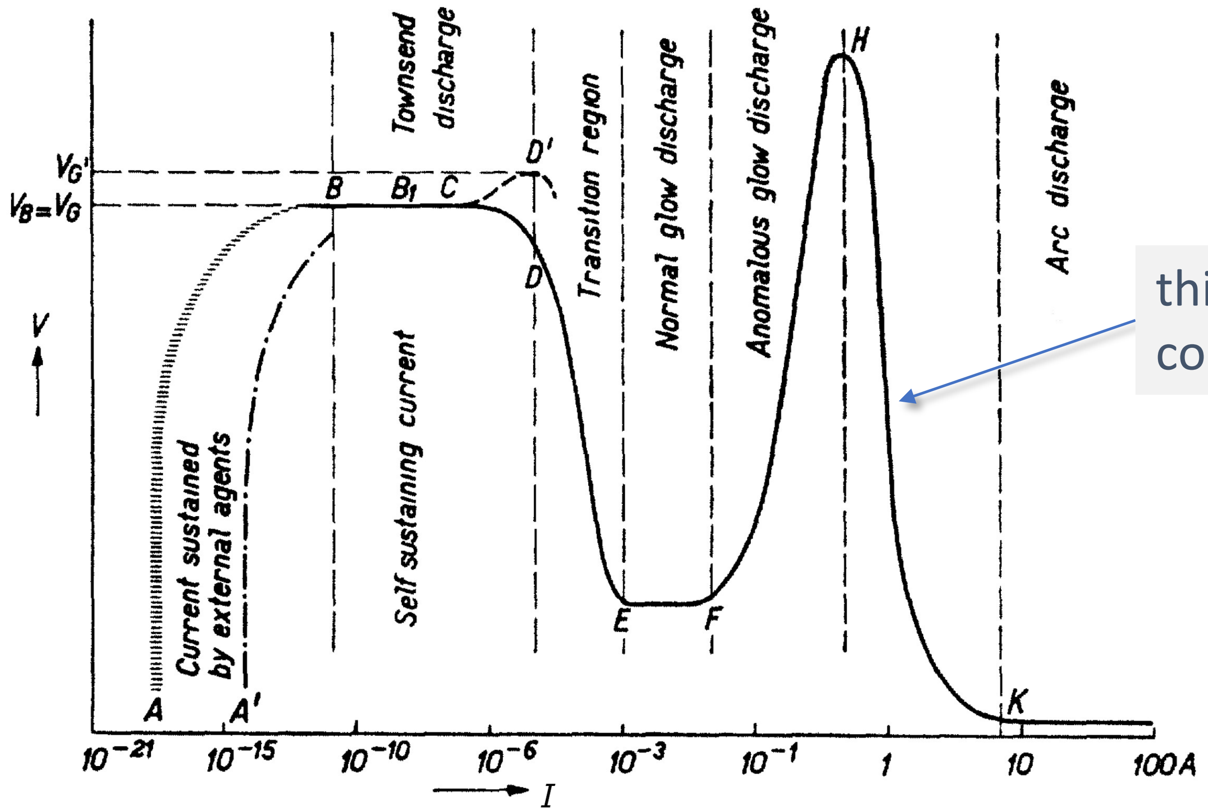


Alessandro Volta, ca. 1765

J. Priestley, *The History and Present State of Electricity*, London 1766

A. Anders, *IEEE Trans. Plasma Sci*. 31, 1052 (2003), and *Cathodic Arcs*, Springer, NY 2008, 2026.

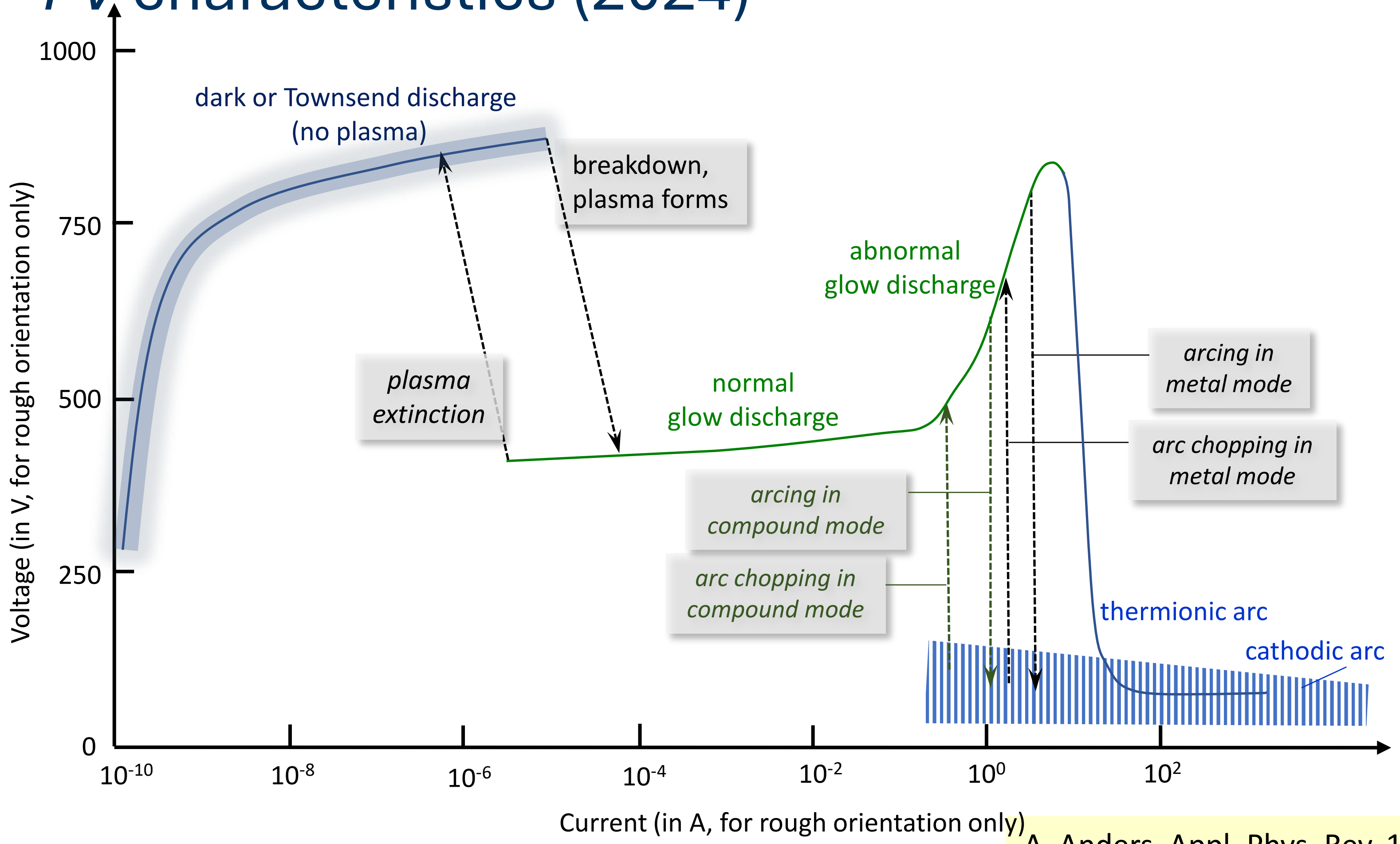
Classic *I-V* characteristics (1940)



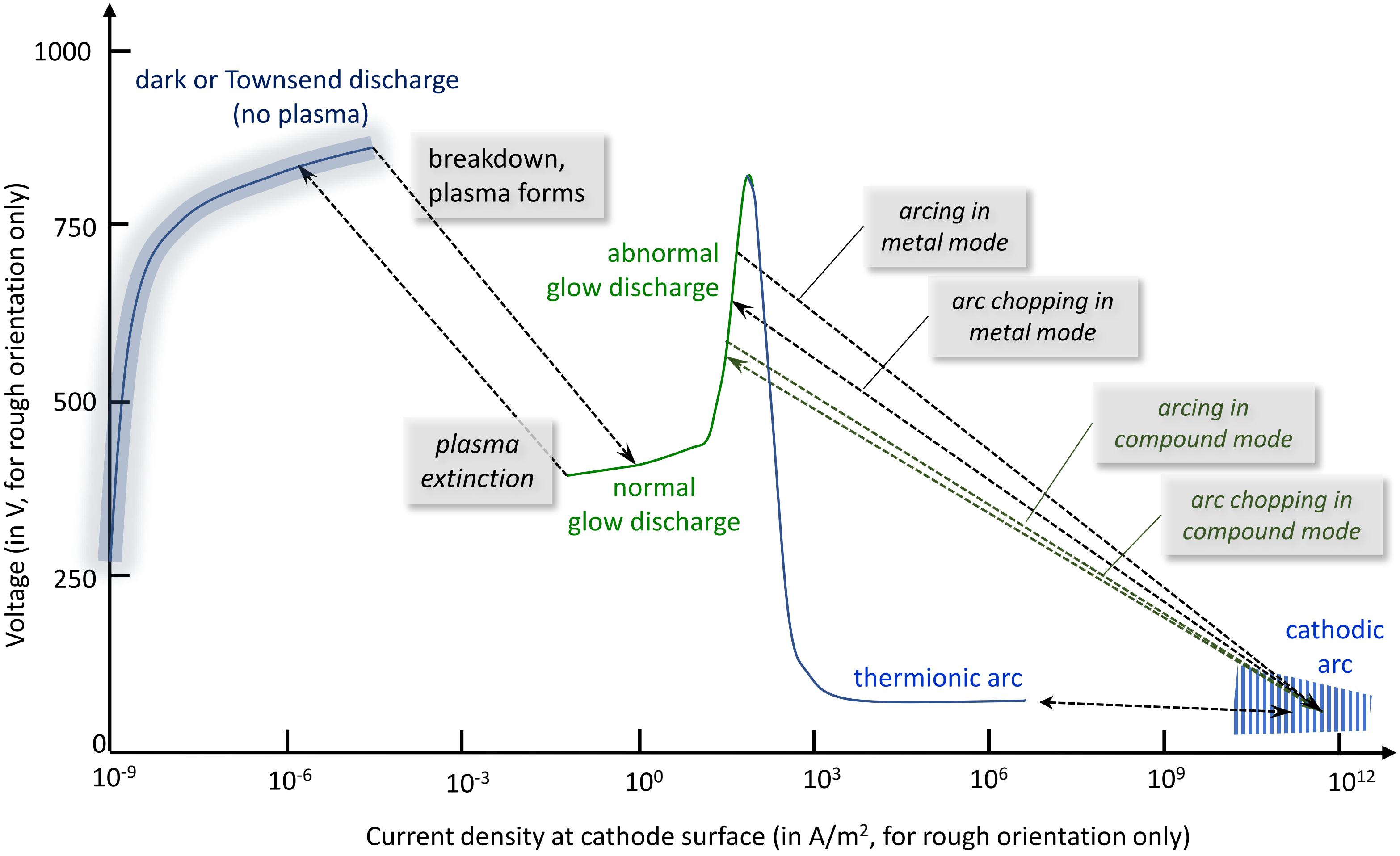
this smooth transition is only correct for thermionic arcs

M.J. Druyvesteyn, F.M. Penning, Rev. Mod. Phys., 12 (1940) 87-174.
copied by: J.M. Meek, J.D. Craggs, Electrical Breakdown of Gases, Clarendon Press, Oxford, 1953.

I-V characteristics (2024)



A. Anders, Appl. Phys. Rev. 11, 031310 (2024).



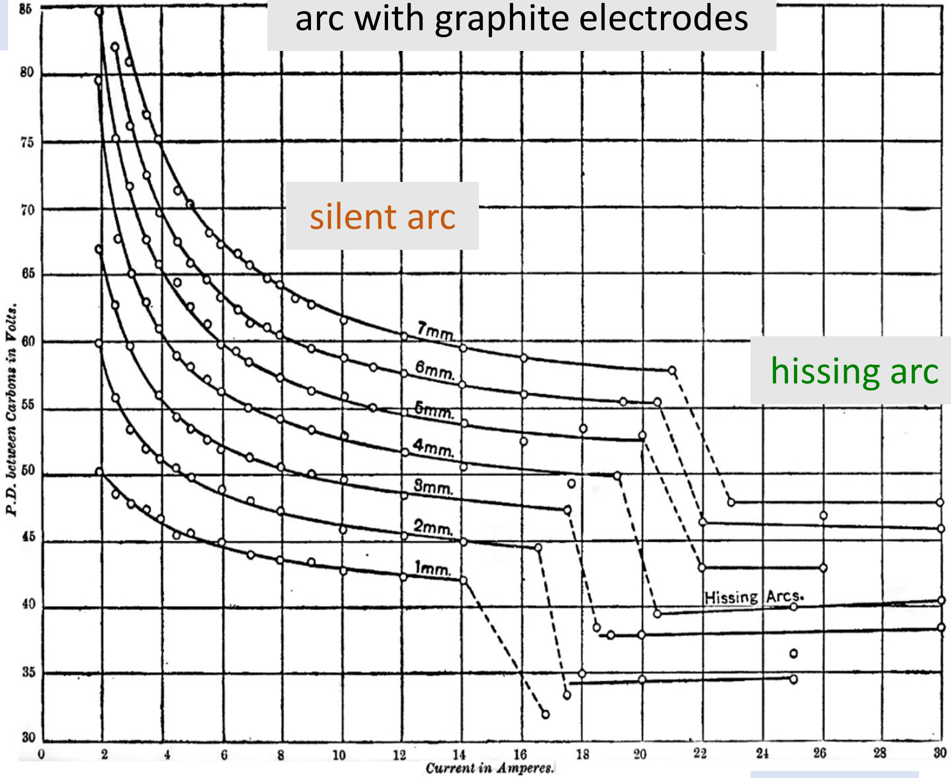
A. Anders, Appl. Phys. Rev. 11, 031310 (2024).

A piece of history: The thermionic to cathodic arc transition

Hertha Ayrton *(1854–1923)*

- *the first woman member of the Institute of Electrical Engineers of the UK (1899)*
- *the first woman nominated to be a Fellow of the Royal Society of London (1902); however, she was held to be ineligible "**because she is a married woman**".*

Hertha Ayrton, Portrait at Girton College, University of Cambridge [Wikipedia]

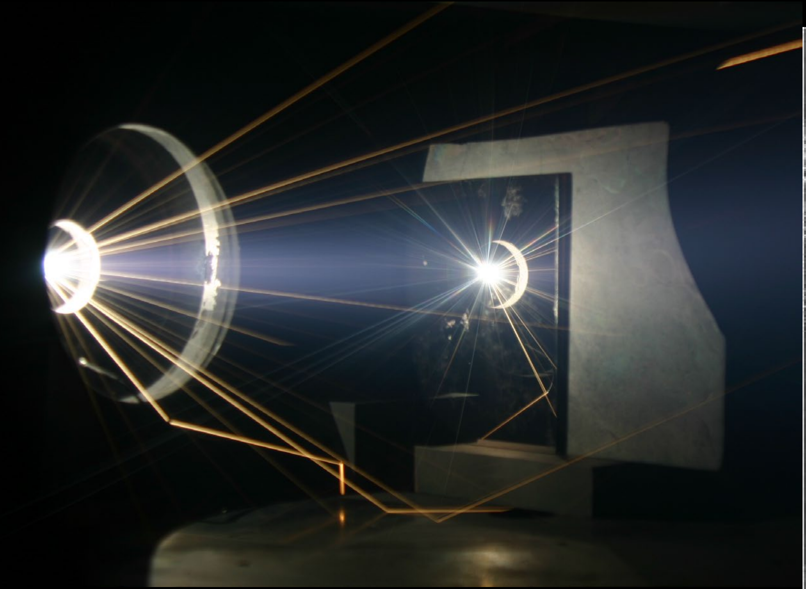


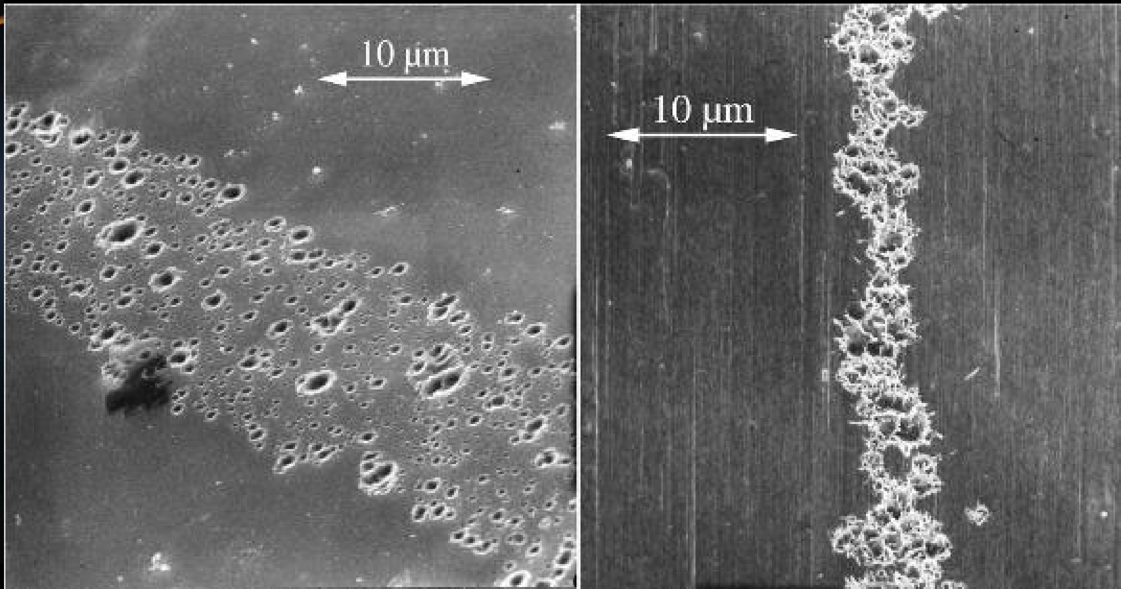
H. Ayrton, The Electric Arc. The D. Van Norstrand Company, London, 1902.

From Thermo-Field to Explosive Emission

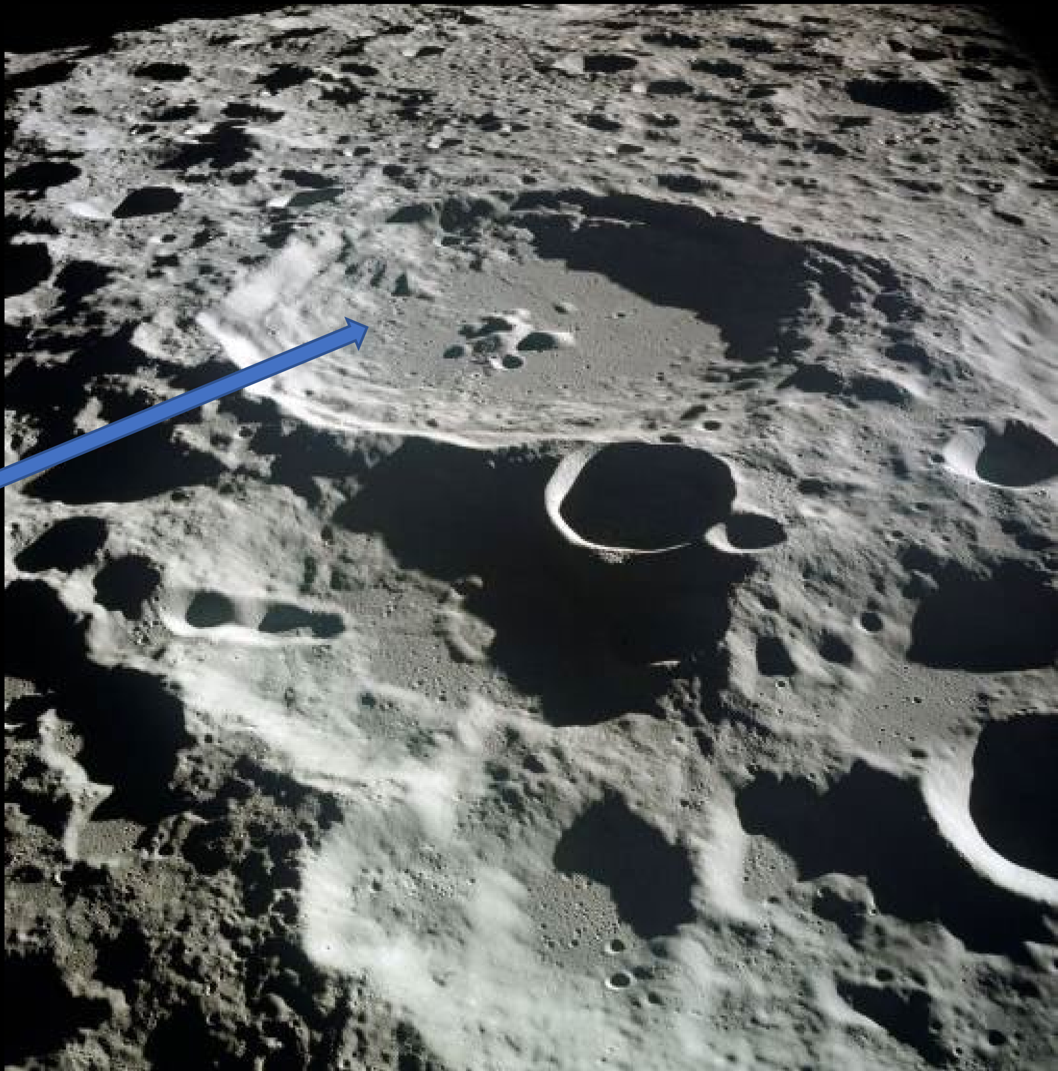
Positive feedback leads in electron emission process to thermal runaway:

- Under thermo-field conditions, some locations get hotter than others, they emit more electrons and get heated more, which means they emit even more, etc.
- those locations “explode” on ns-time scale; they emit not only electrons but plasma; locations are called cathode spots, associated with “arcing”

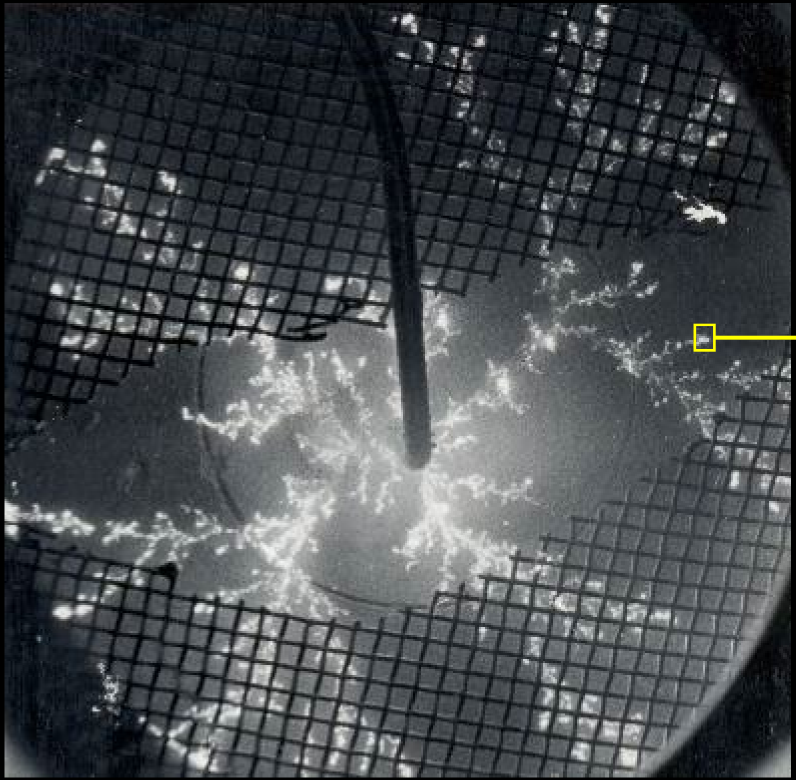




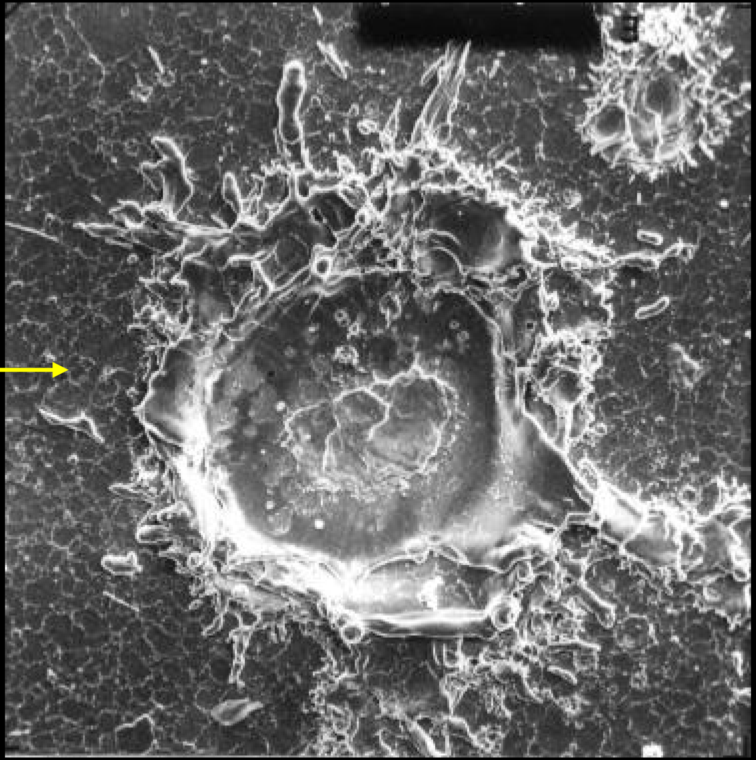
Craters are the result of short duration, high power density



Effects of short duration, high power density

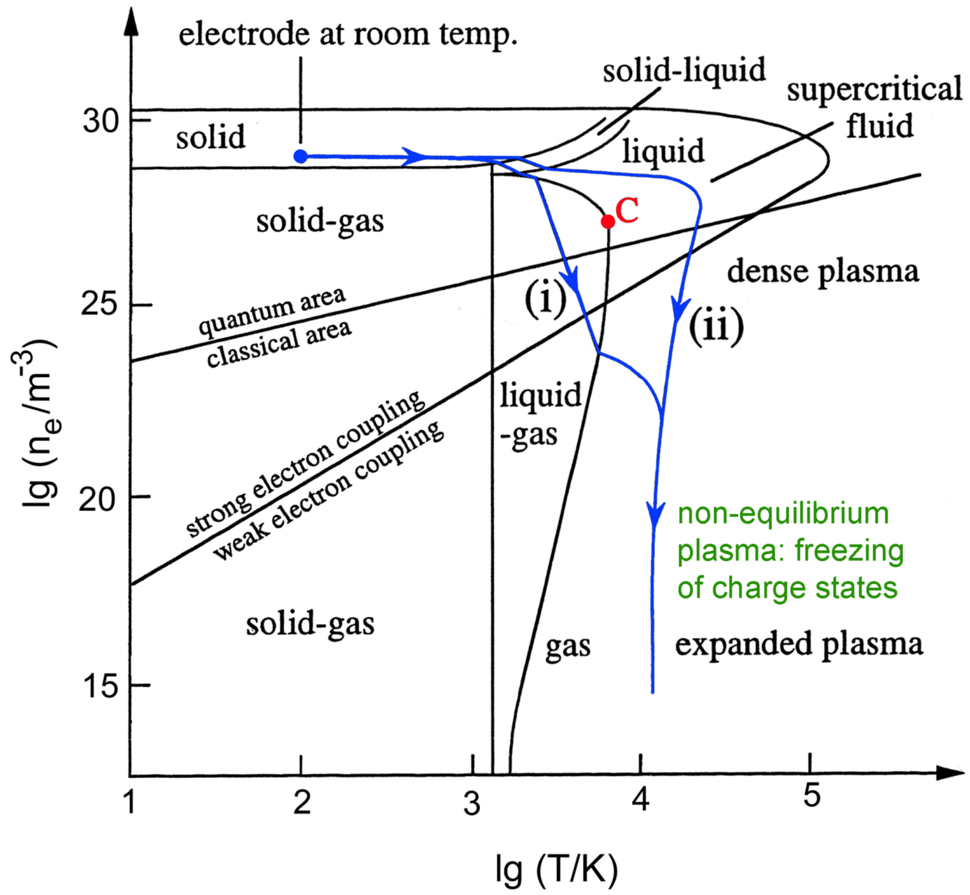


pulsed cathodic arc, looking at cathode



electron microscope image
of cathodic arc cathode

Path of the Cathode Material in the *n-T* Phase Diagram



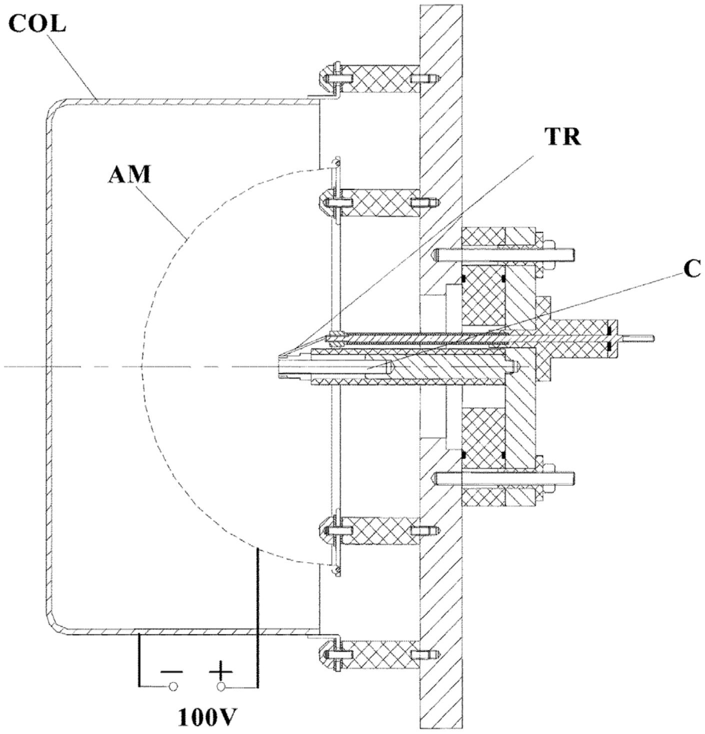
A. Anders, Plasma Sources Sci. Technol. **21** (2012) 035014.

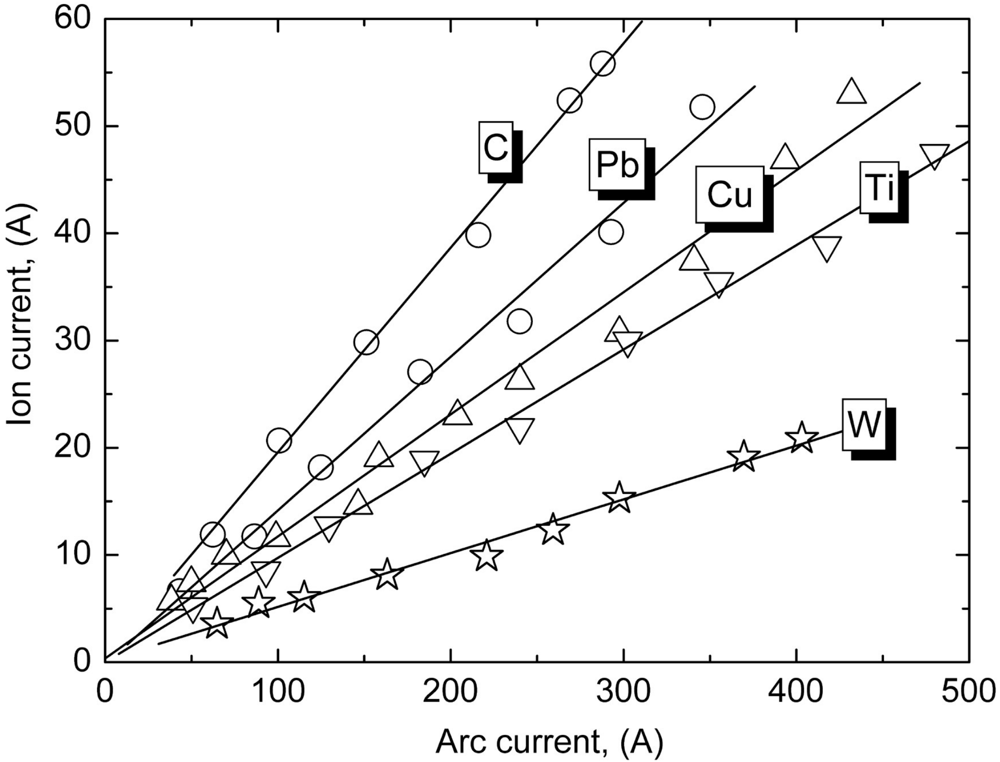
Properties of cathodic (vacuum) arc plasmas

- Plasma expands from near solid state density (10^{27} m^{-3}) in the cathode spot to very rarified plasma far from spot
- *Jüttner's formula*: in absence of magnetic field $$n(r) \approx \gamma I_{arc} / (r + r_{spot})^2$$ $$\gamma \approx 10^{13}\ \mathrm{A^{-1}m^{-1}}\ \text{(for copper)}$$
- electron temperature near spot 2-4 eV
- range of plasma expansion (ion) velocity far from the spot $$v_i \approx 0.8 - 2.2 \times 10^4\ \mathrm{m/s}$$
- positive ions move *FROM* the cathode, driven by pressure gradients
- → Electron current > net arc current

A. Anders, *Cathodic Arcs*, Springer, NY 2008, 2026.

Ions of vacuum arcs move into the “electrically wrong” direction





A. Anders, et al., IEEE Trans. Plasma Sci. 33, 1532 (2005).

Cohesive Energy Rule

The vacuum arc voltage scales linearly with the cohesive energy of the cathode material.

$$V_{arc} \approx V_0 + AE_{CE}$$

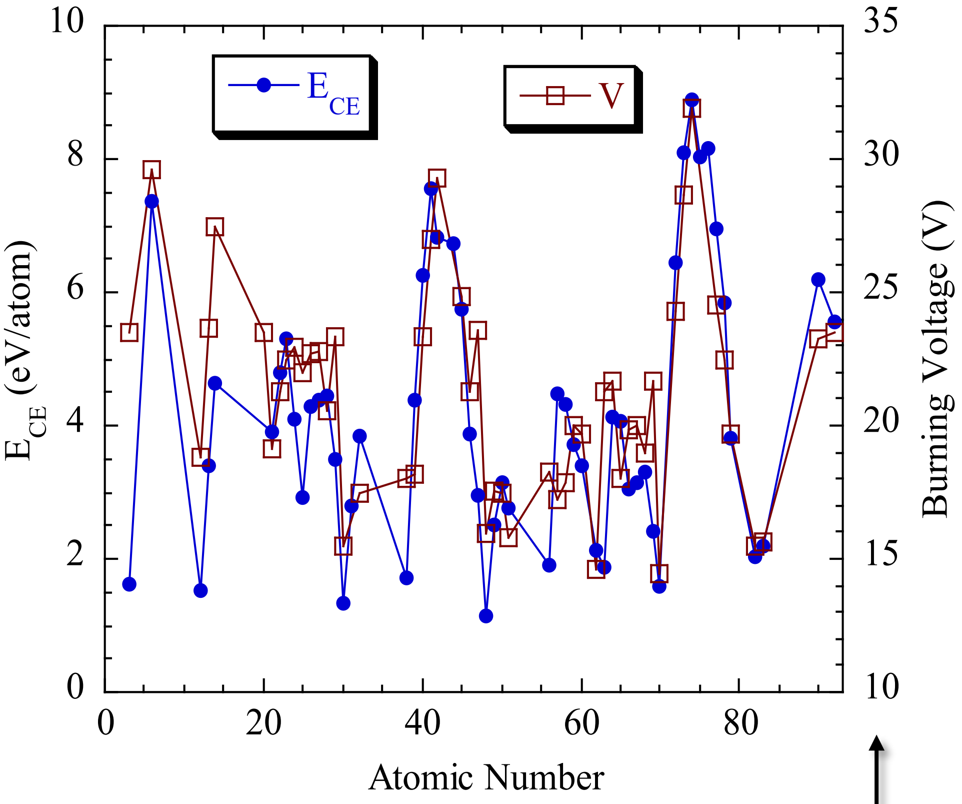
experiments:

$V_0 = 14.3$ V

$A = 1.69$ V/(eV/atom)

Cohesive energy = the energy needed to free an atom from the solid.

A. Anders *et al*, J. Appl. Phys. 89 (2001) 7764



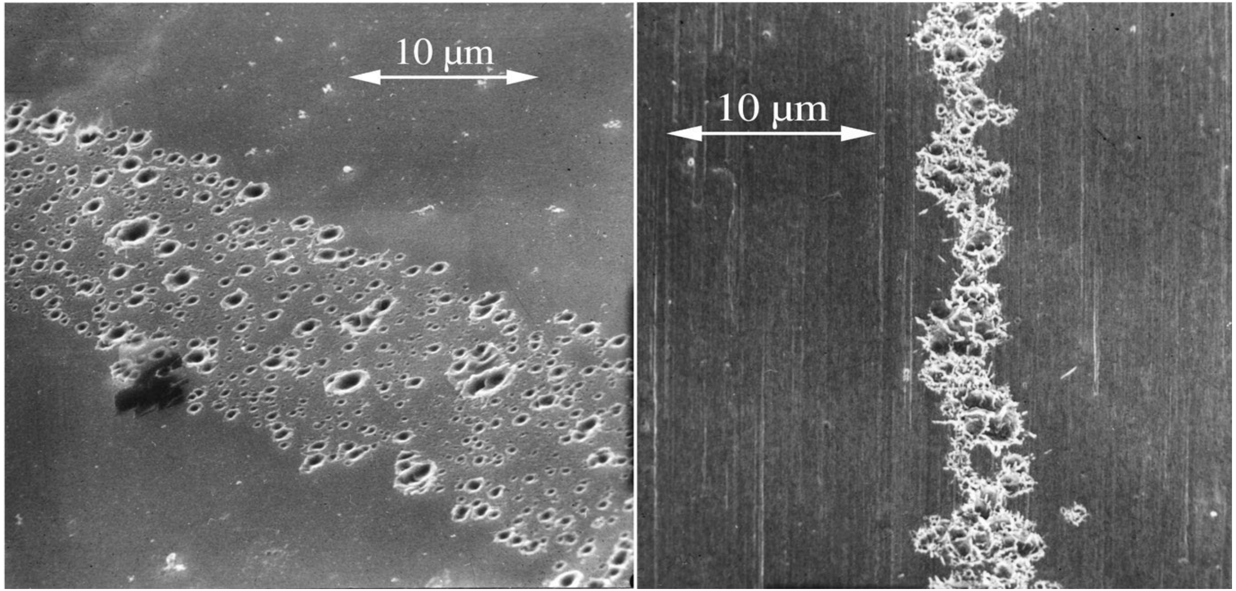
Note this voltage level in relation to the sheath voltage when discussing unipolar arcs.

Arc spots in the absence and presence of plasma

Absence of plasma → spots appear by "breakdown" at high voltage.

Presence of plasma → spots appear under the sheath.

In both cases, the high electric field facilitated spot formation.



arc traces on oxidized and clean metal cathode surfaces

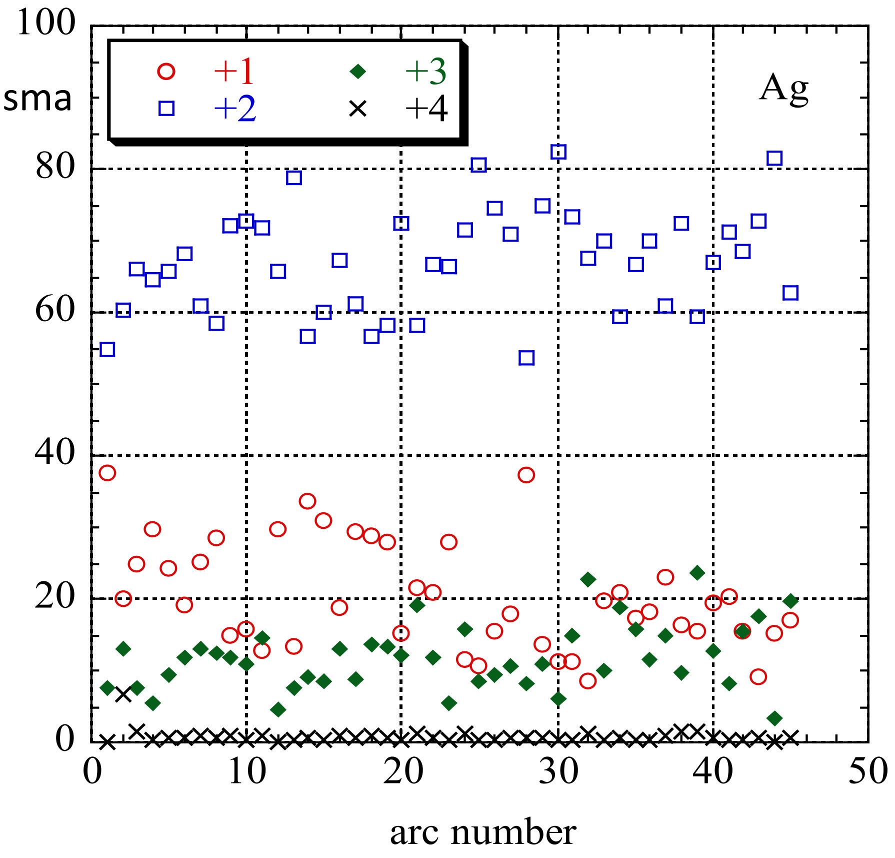
Figures courtesy of B. Jüttner

The key to understanding vacuum arcs are cathode spot processes

Cathode processes are inherently non-stationary

→ Fluctuations due to Explosive Electron Emission and Plasma Formation

Percentage of ion charge state in plasma

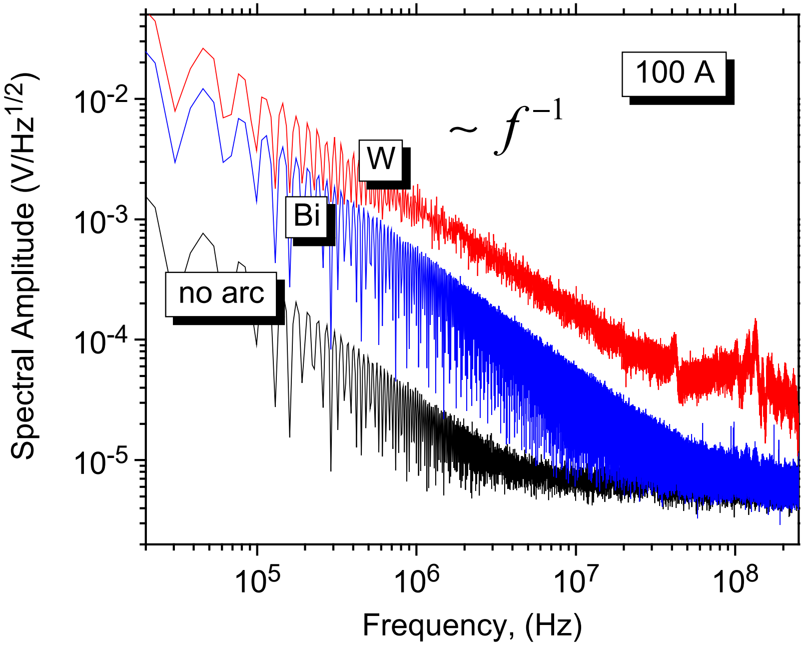


- Fluctuations are present in practically all parameters (voltage, density, ion charge state, plasma temperature,…)
- Example here: Sampling of ion charge states of silver arcs in vacuum

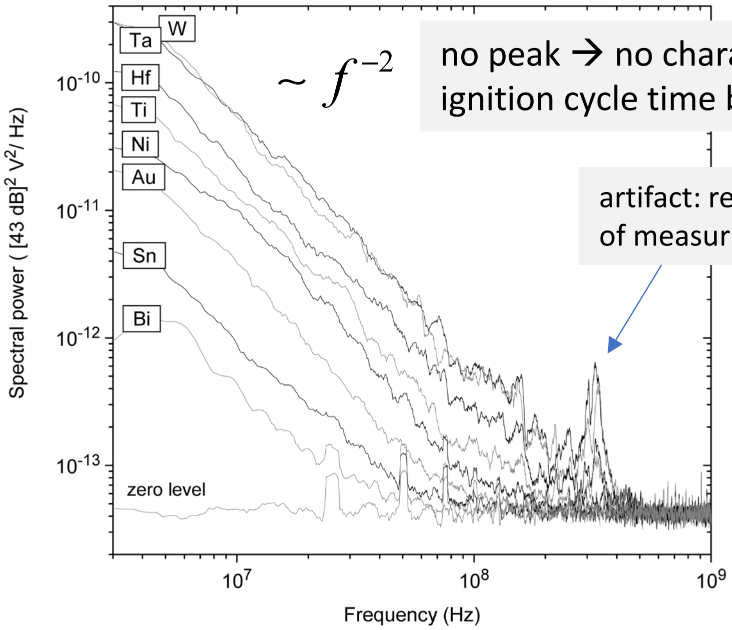
A. Anders, IEEE Trans. Plasma Sci. 27 (1999) 1060.

Analyzing spectra of vacuum arc voltage fluctuations

- An object is self-similar (invariant with scaling, a **fractal**) if it is reproduced when magnifying some portion of it.
- Power laws are self-similar and indicators for fractals.



A. Anders, et al., Appl. Phys. Lett., 86 (2005) 211503.



no peak → no characteristic ignition cycle time but fractal

artifact: resonance of measuring circuit

J. Rosén, A. Anders, J. Phys. D: Appl. Phys., 38 (2005) 4184.

High-speed photography of cathodic arc plasmas

Dynamics of cathode spots: carbon arc as seen with a high-speed framing camera
 arc current up to 5 kA, 200 ns exposure time per frame

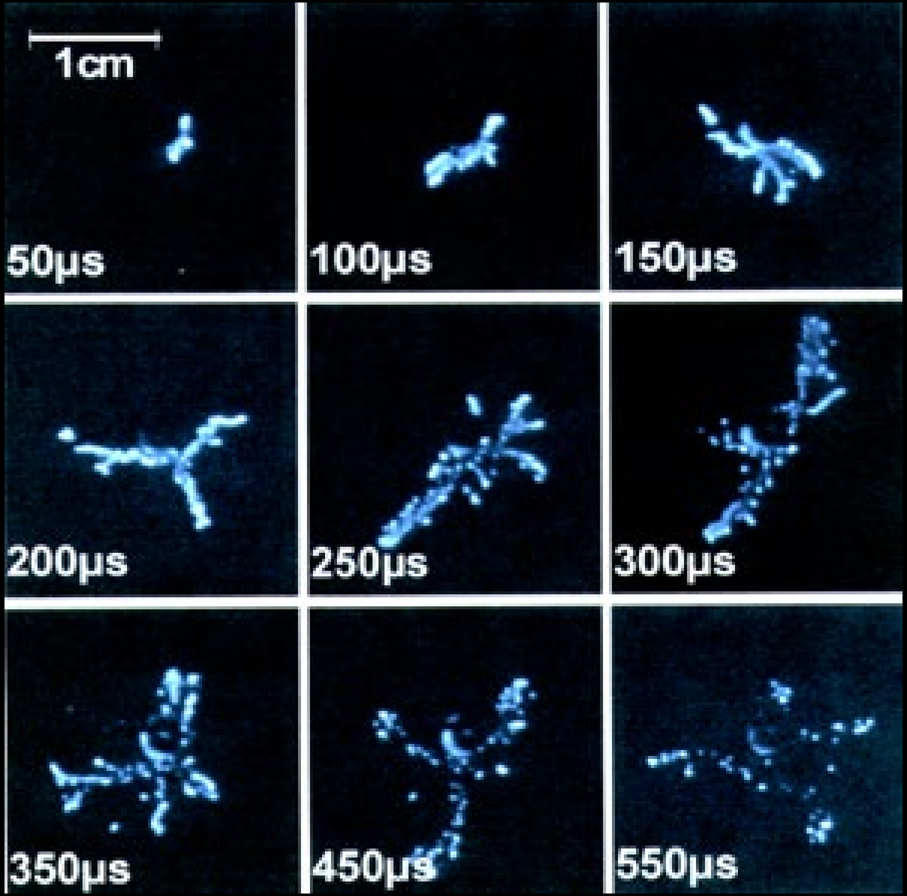
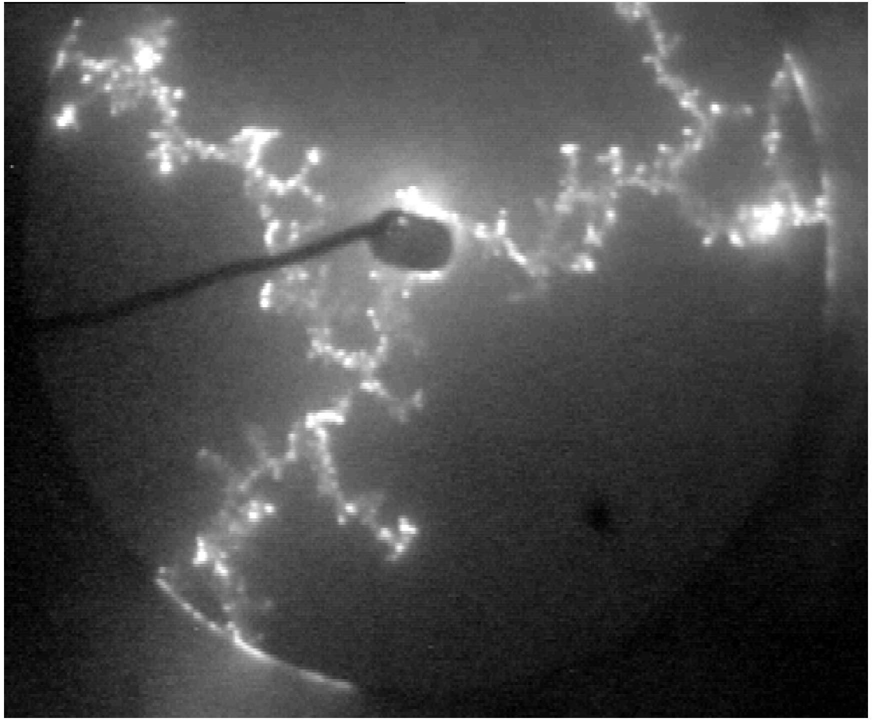


Figure: Courtesy of P. Siemroth and T. Schülke (about 2000)

Magnetically steered vacuum arc

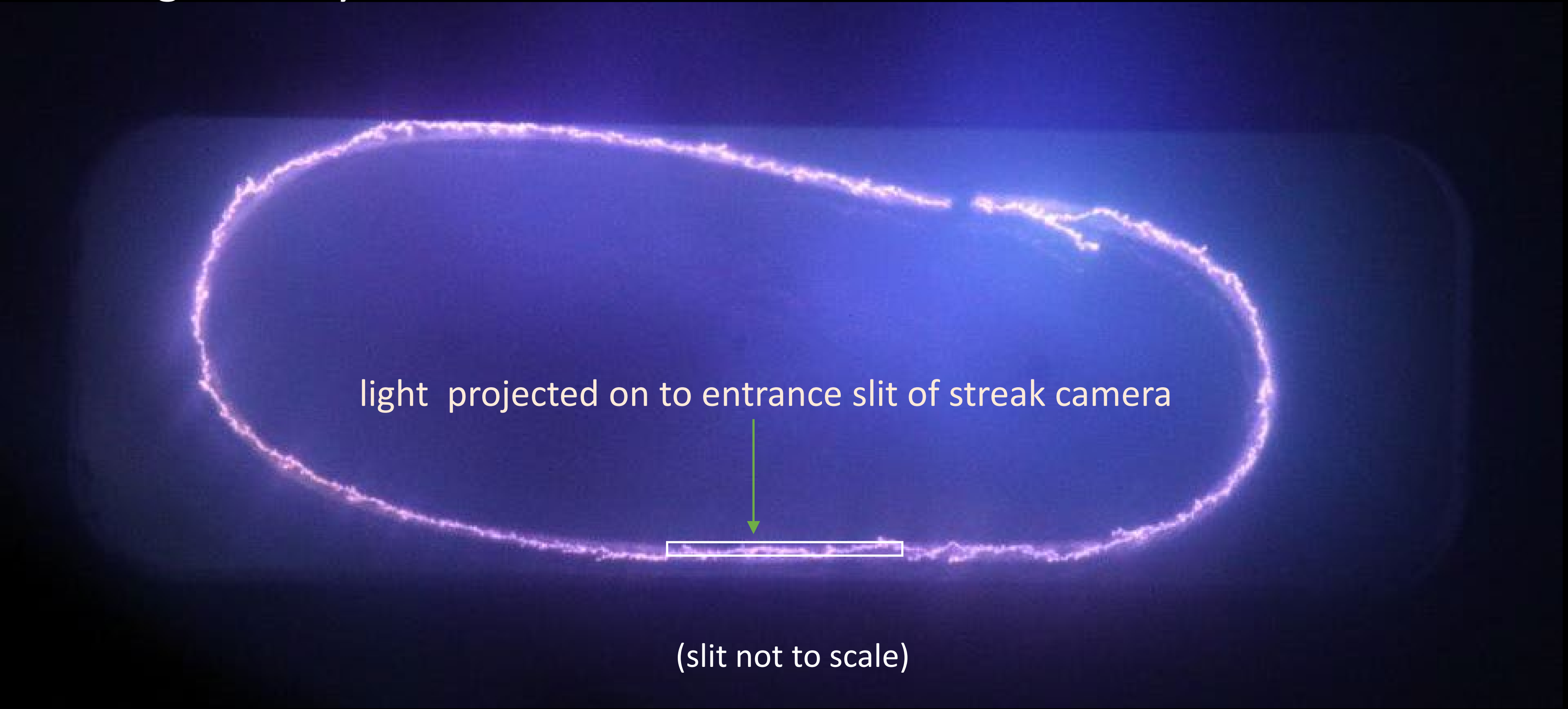


vacuum arc spots, no extern magnetic field but spots affect each other mutually

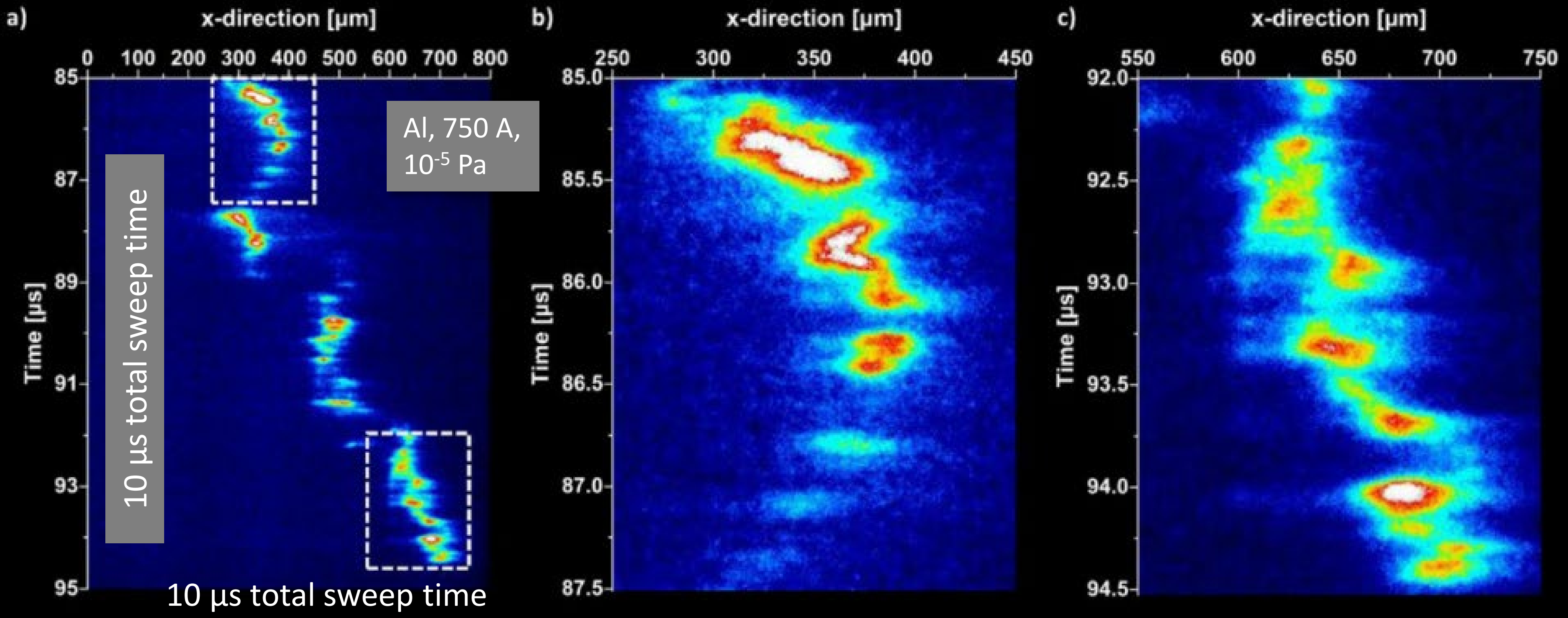
cathodic (vacuum) arc with magnetic field, as used in deposition of films and coatings

http://nanoarctech.com/equipments/cathodic-arc-pvd/

Magnetically steered vacuum arc



Streak camera study of vacuum arc cathode spots

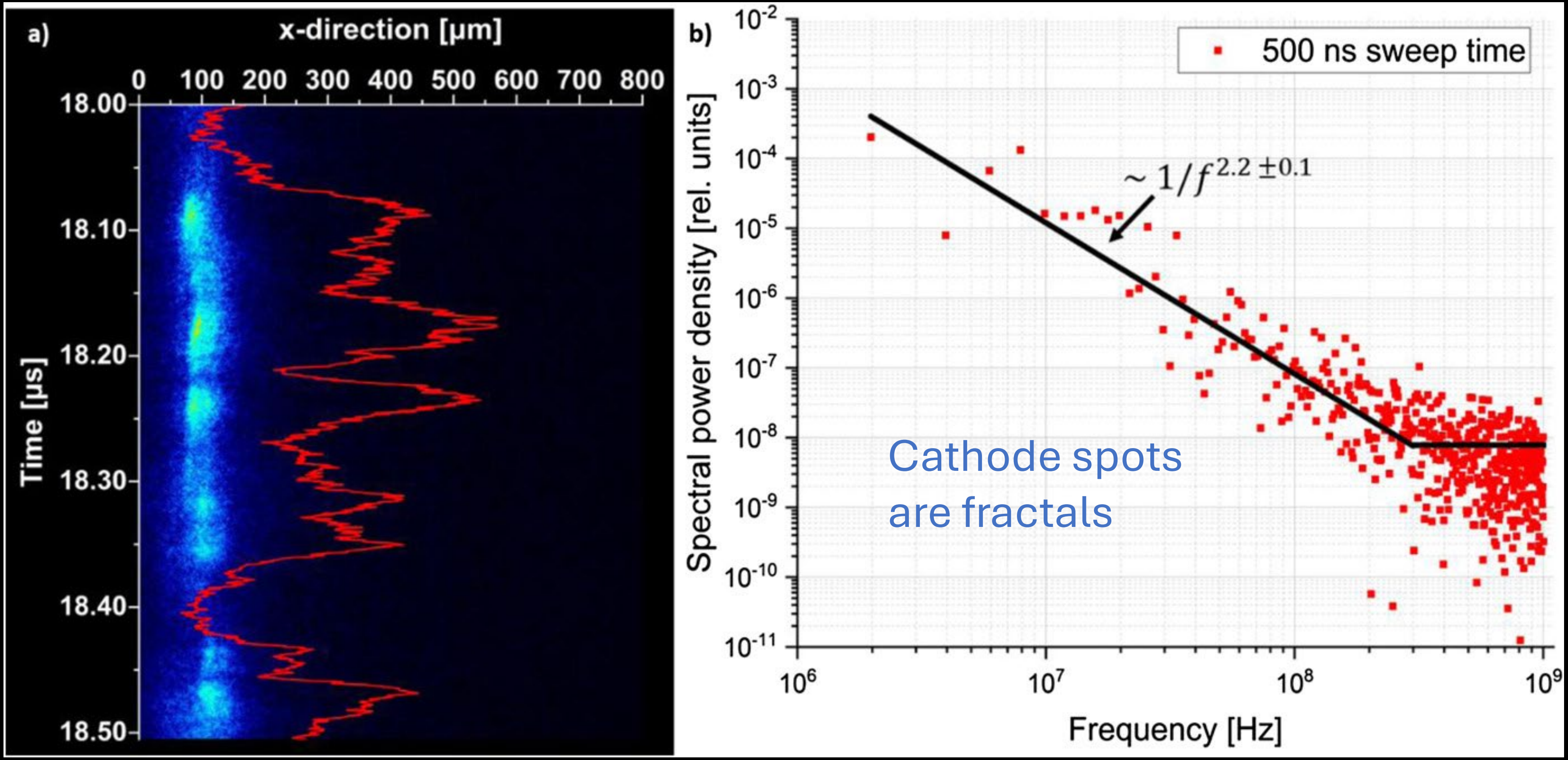


FFT of emitted light analysis→ spots do not show periodic but self-similar (fractal) features

K. Oh, et al., Plasma Sources Sci. Technol., 30 (2021) 095005.

Streak camera study of fluctuations

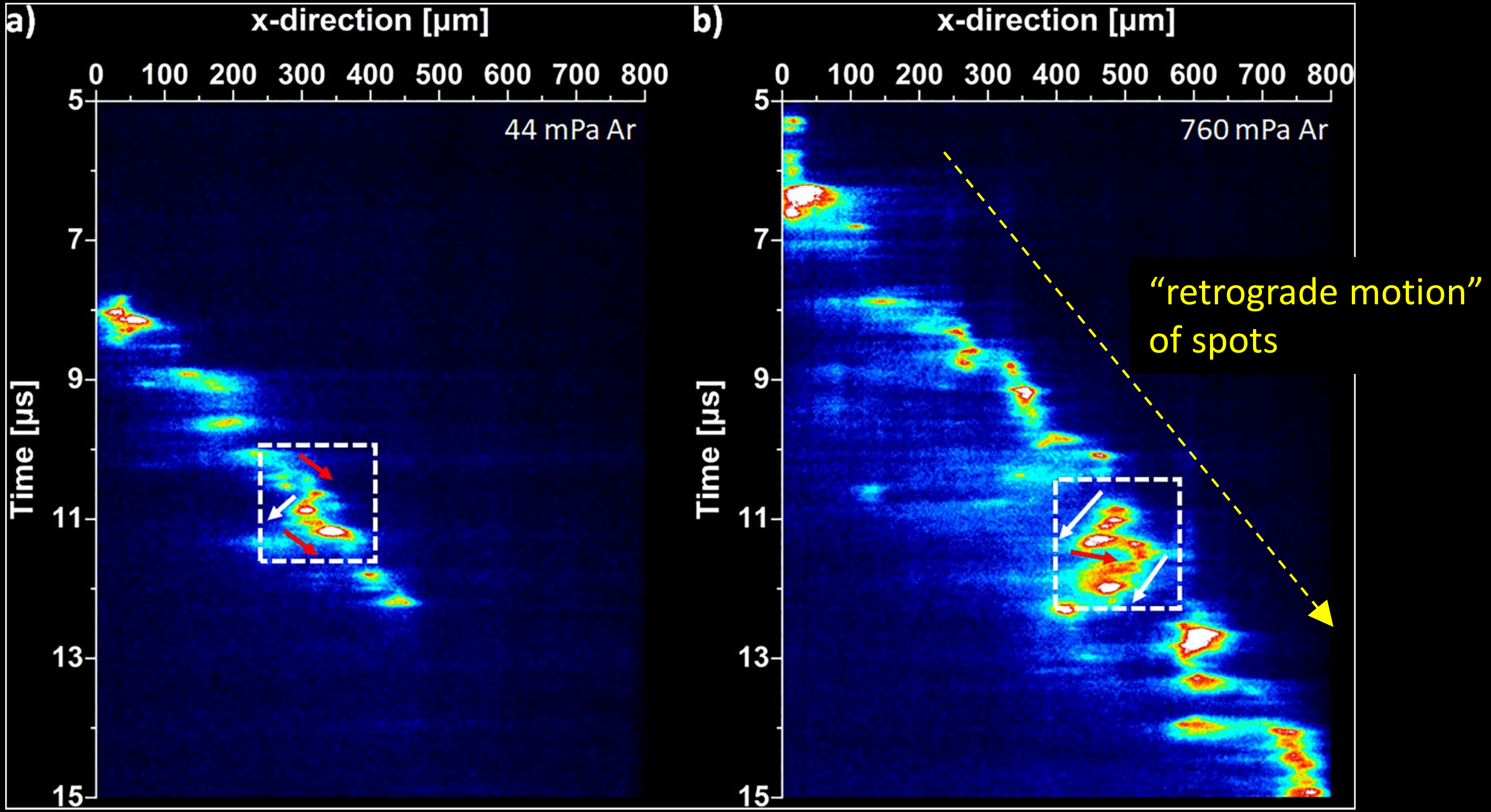
500 ns total sweep time



K. Oh, *et al.*, Plasma Sources Sci. Technol., 30 (2021) 095005.

Cathode spot fluctuations, **argon** background

Al, 750 A

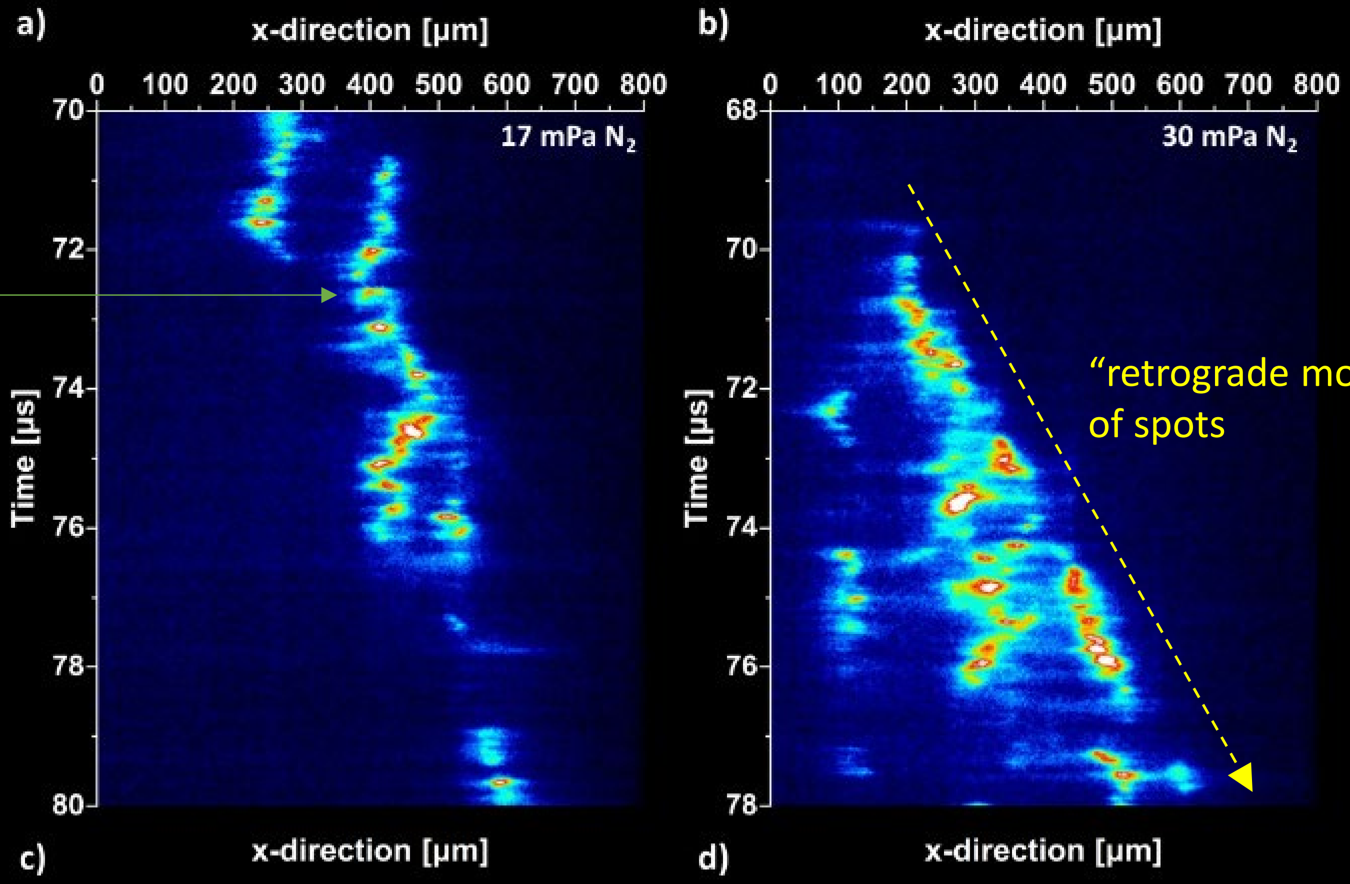


K. Oh, *et al*., J. Appl. Phys., 130 (2021) 183304.

Cathode spot fluctuations, **nitrogen** background

Al, 750 A

ignition near the previous site

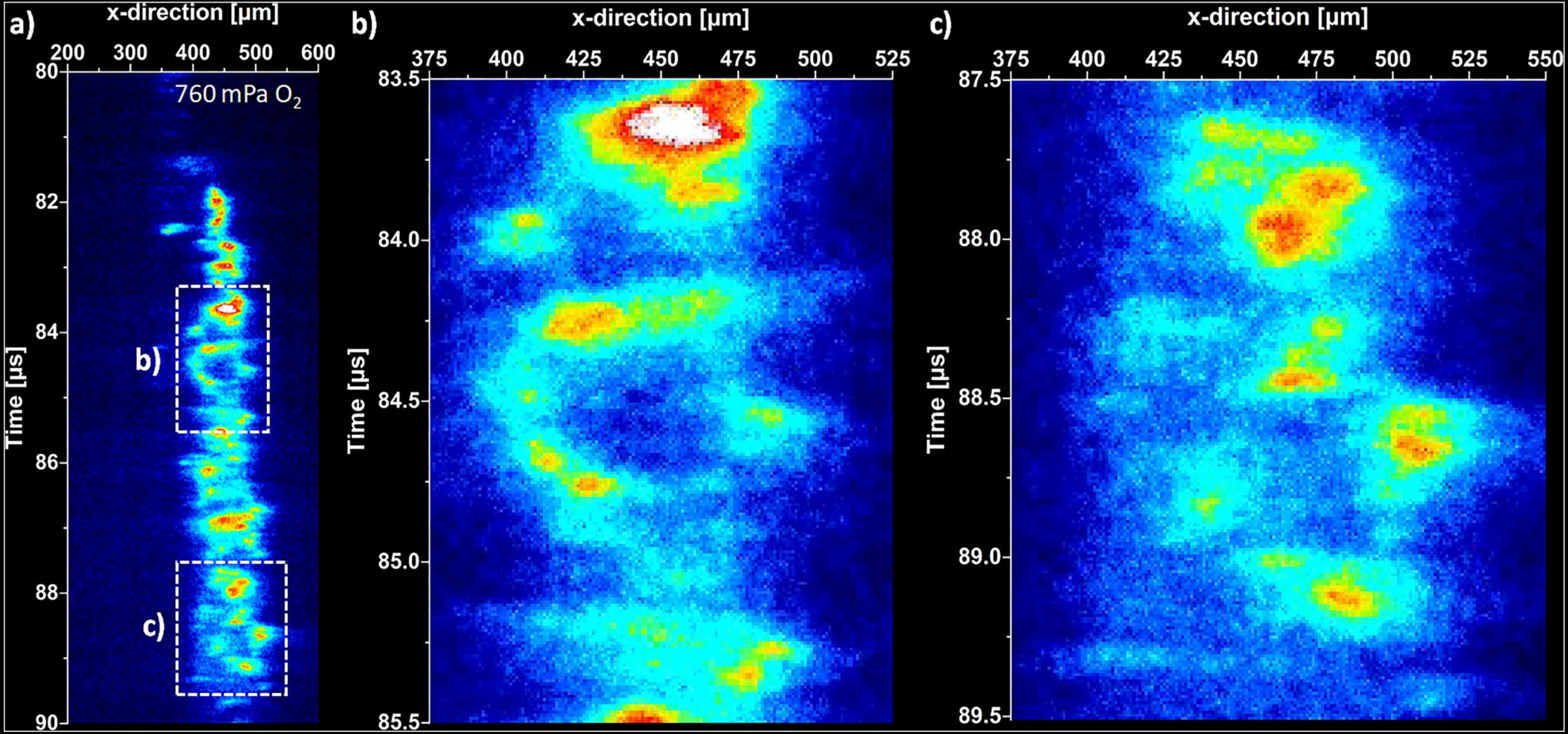


"retrograde motion" of spots

K. Oh, *et al.*, J. Appl. Phys. 130 (2021) 183304.

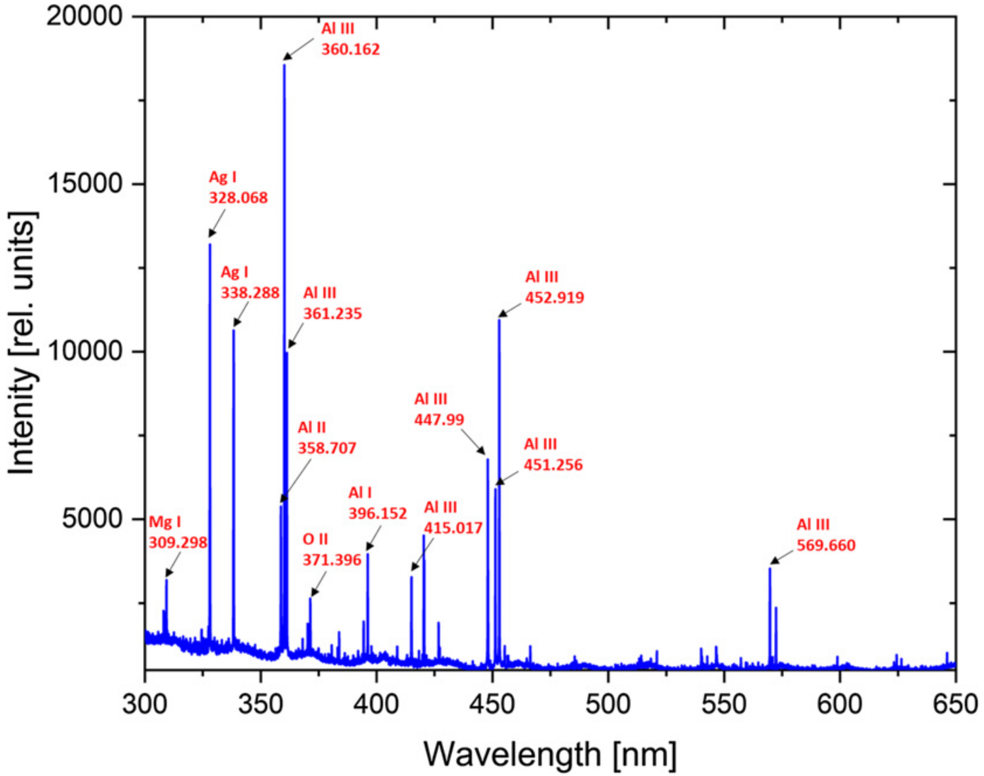
Cathode spot fluctuations, **oxygen** background

Al, 750 A



K. Oh, *et al.*, J. Appl. Phys., 130 (2021) 183304.

Physical resolution limits when using light emission



Einstein coefficient of the Al III transitions

$$(\Delta t)^{-1} = A_{ij} = 1.3 - 2.5 \times 10^{8}\ \text{s}^{-1}$$

and

transverse ion velocity $\quad v_{\perp i} \approx 10^{3}\ \text{m/s}$

smearing out of emission profile

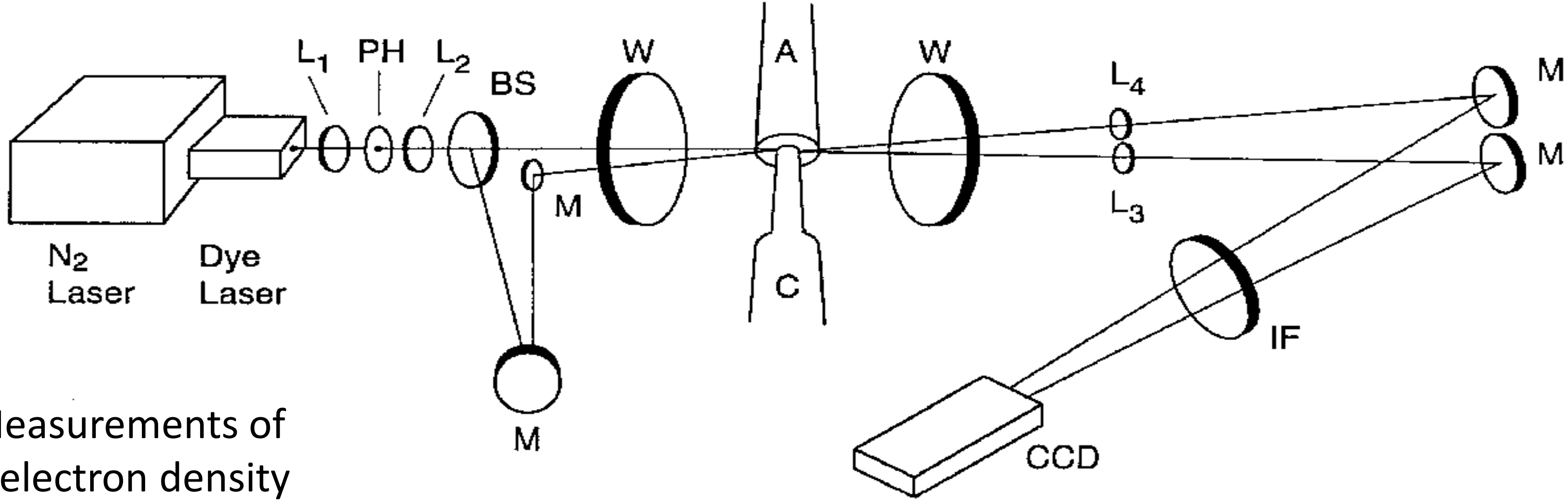
$$\Delta s = \Delta t \times v_{\perp i} \approx 5 \times 10^{-5}\,\text{m} = 5\ \mu\text{m}$$

→in optical emission, ultimate resolution limits are 5 ns and 5 µm

K. Oh, *et al.*, Plasma Sources Sci. Technol., 30 (2021) 095005.

Laser plasma diagnostics of vacuum arc plasma

Differential laser absorption photography and spectrometry does not rely on optical emission

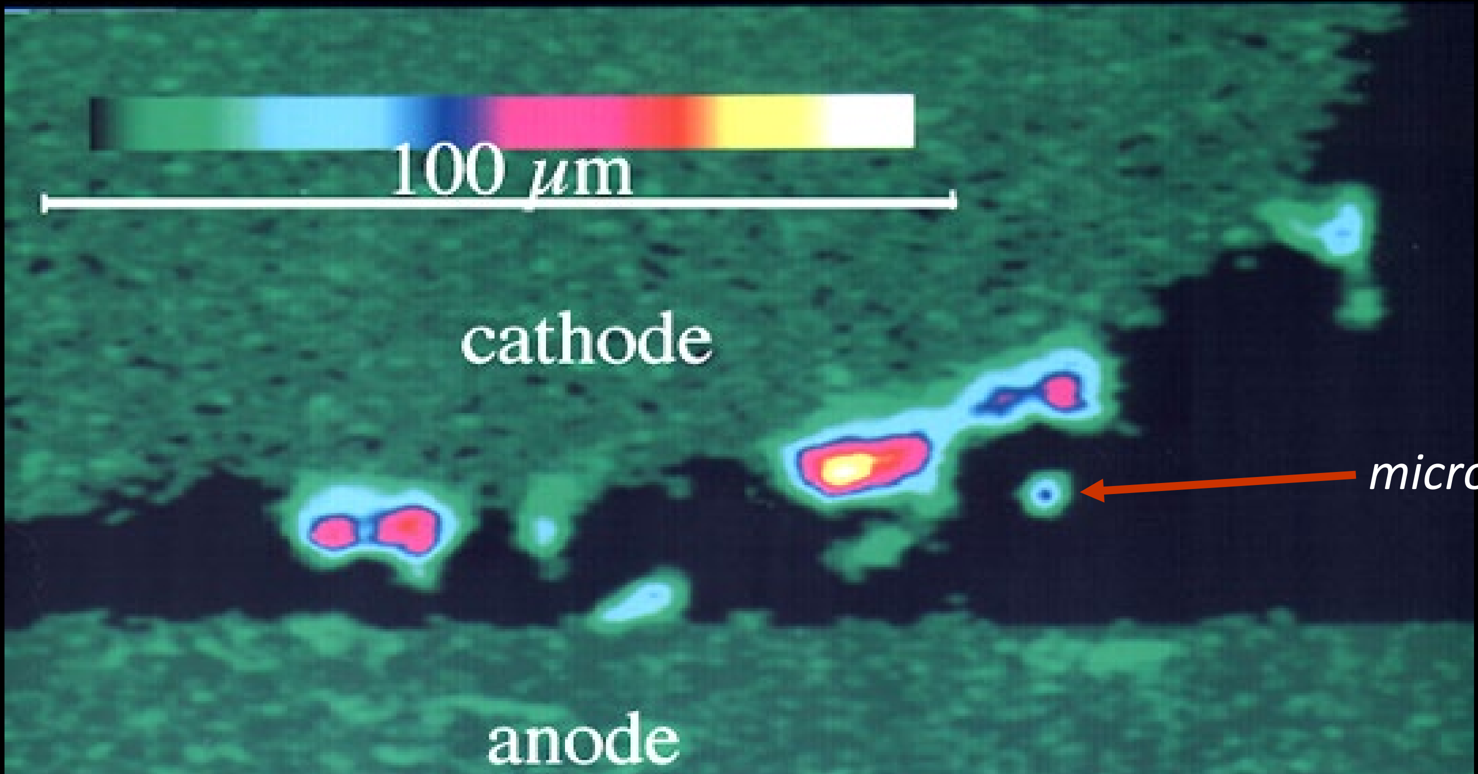


Measurements of
- electron density
- temporal development (400 ps laser pulses)

To determine
- Current density
- Understanding plasma formation

A. Anders, *et al*, IEEE Trans. Plasma Sci. 20 (1992) 466-472

Vacuum arc spot diagnostic by laser absorption imaging

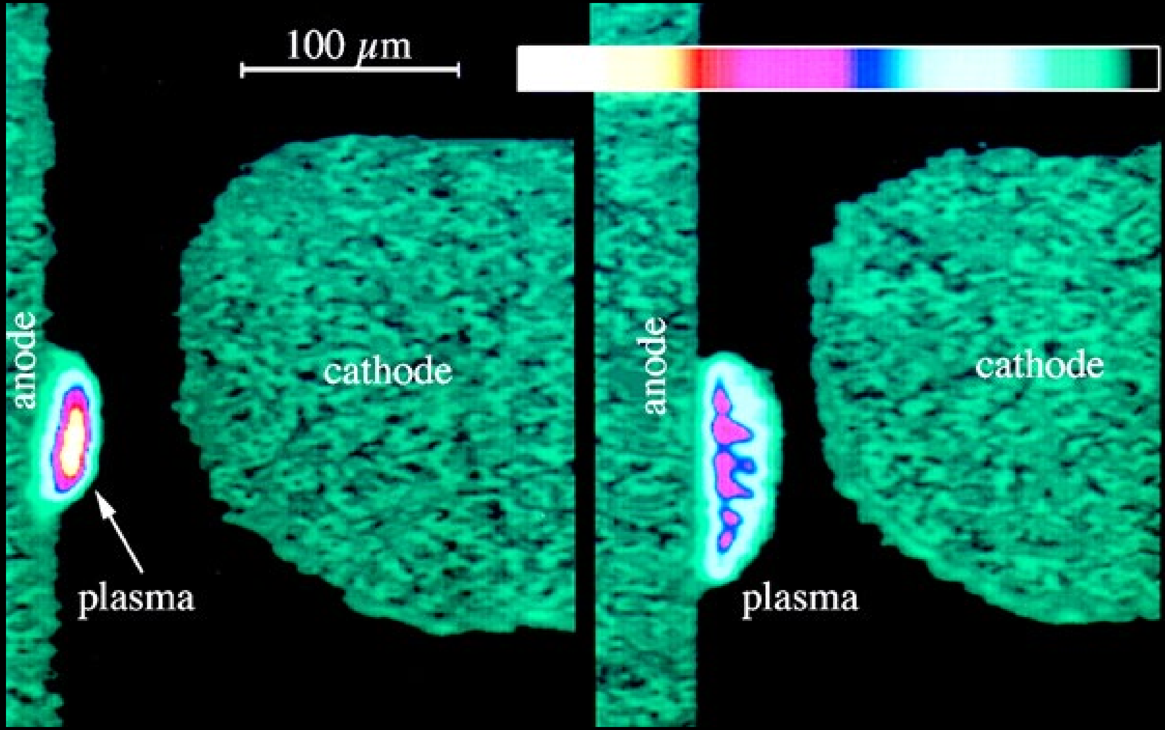


Differential absorption photography, copper cathode, UHV conditions, arc current 90 A, 232 ns after arc ignition, exposure time 400 ps

A. Anders *et al*, IEEE Trans. Plasma Sci. 20 (1992) 466; and IEEE Trans. Plasma Sci. 24 (1996) 69.

High voltage breakdown in vacuum

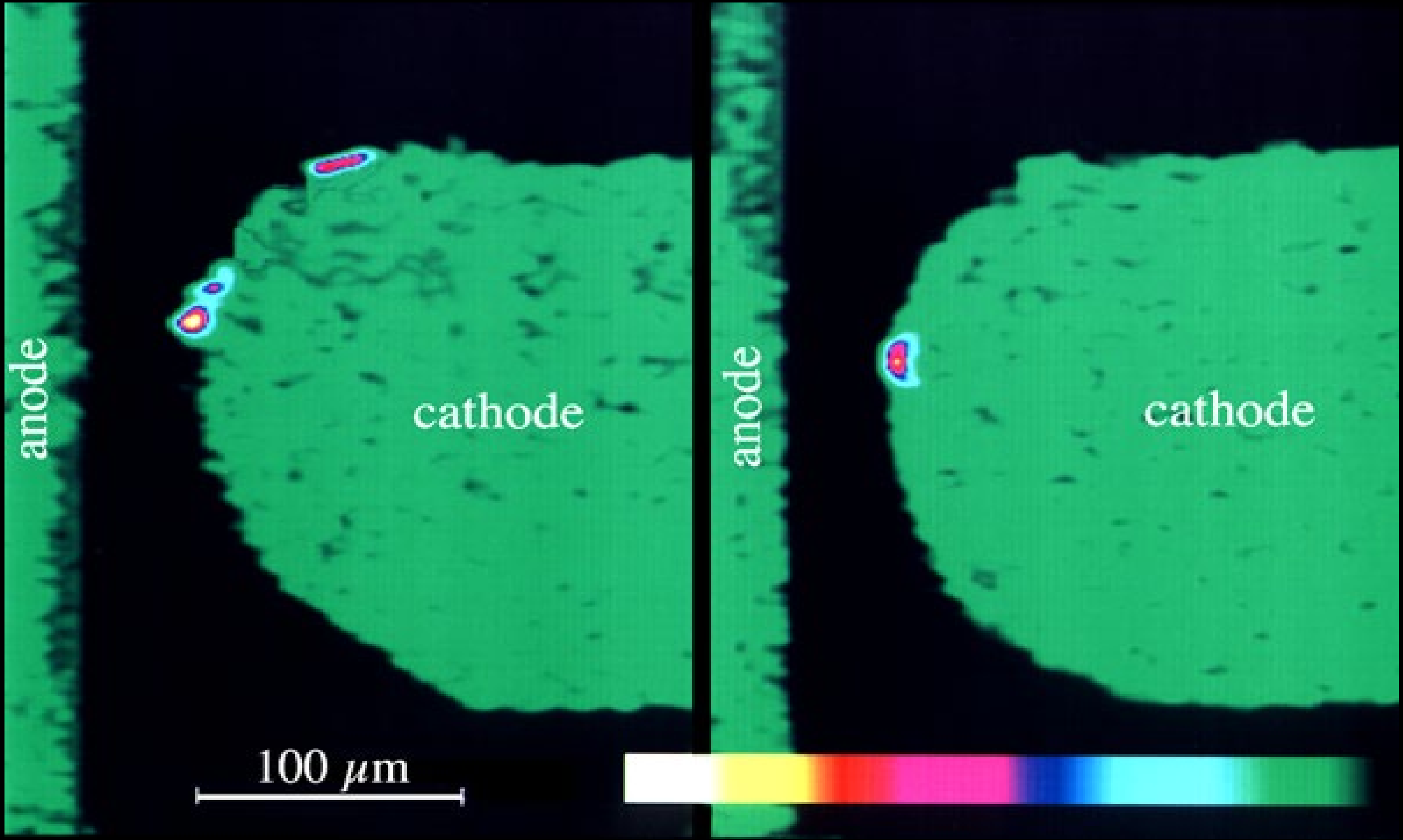
- Laser absorption photography of vacuum breakdown event, Cu, 100 A, time between pictures 3 ns
- Spark phase of the arc: voltage is still high
- field-emitted electrons cause anode plasma that bridges the gap



A. Anders *et al*, IEEE Trans. Plasma Sci. 20 (1992) 466; and IEEE Trans. Plasma Sci. 24 (1996) 69.

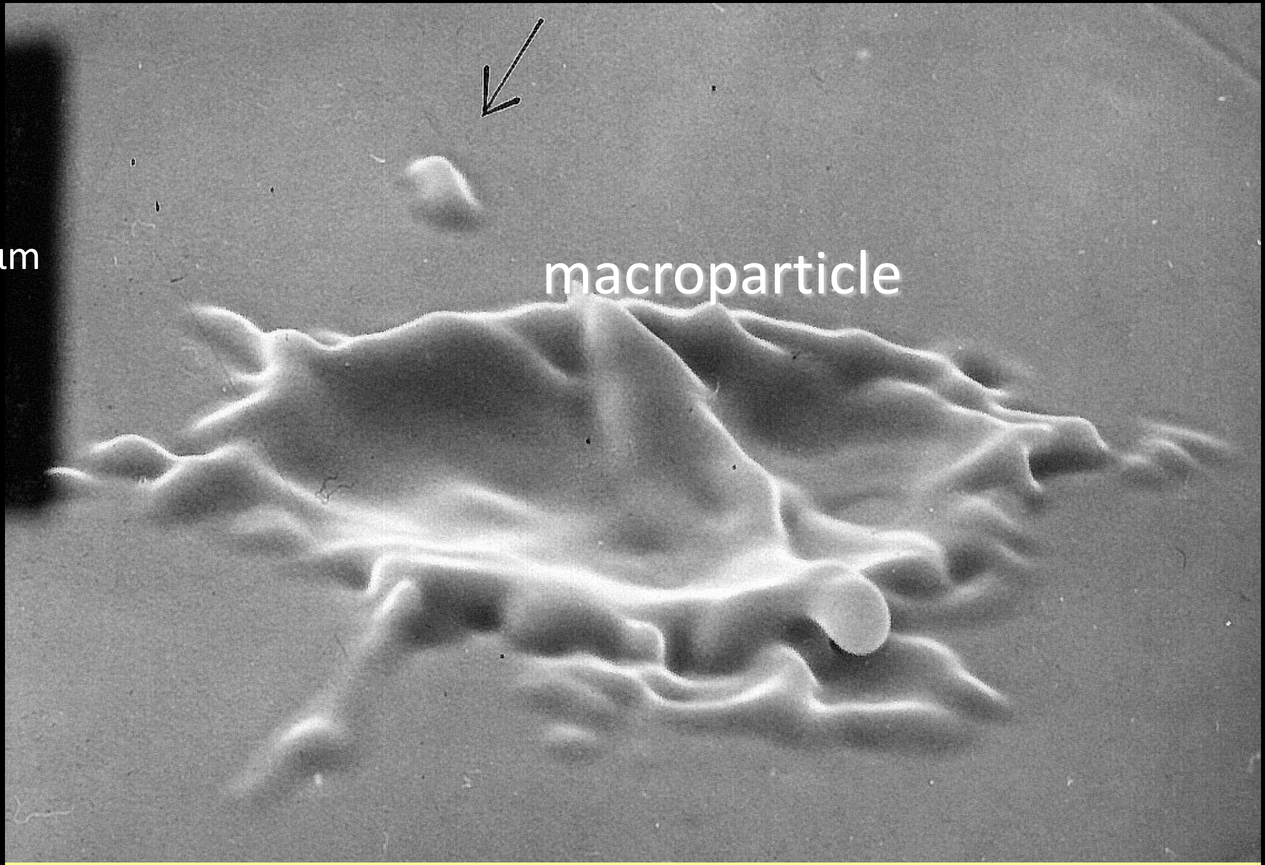
Cathode spot dynamics after plasma bridging

development of cathode spots, observed by absorption photography, Cu, 100 A, Δt between pictures 3ns

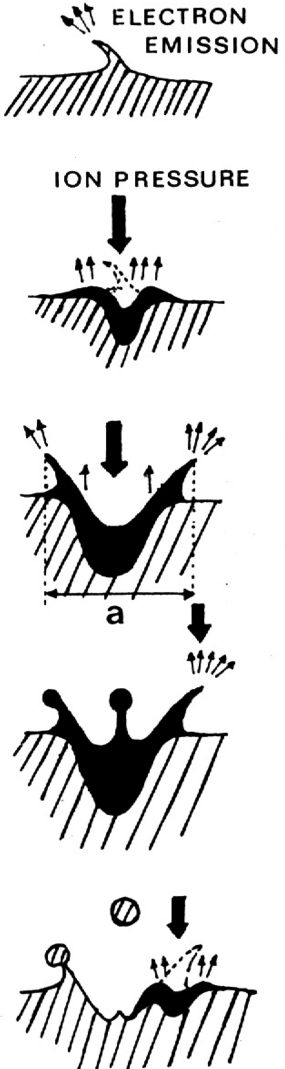


A. Anders *et al*, IEEE Trans. Plasma Sci. 20 (1992) 466; and IEEE Trans. Plasma Sci. 24 (1996) 69.

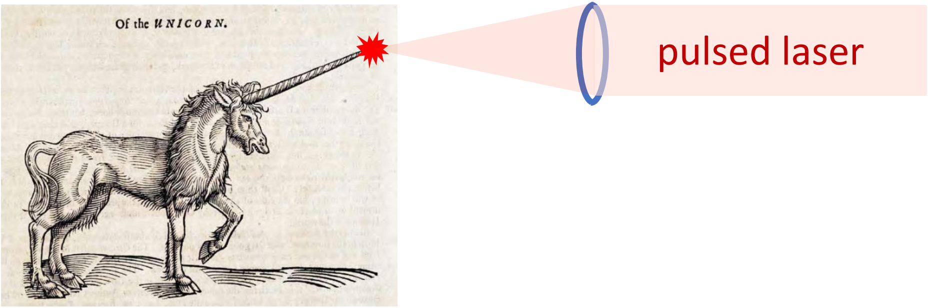
Self-generation of arc ignition conditions

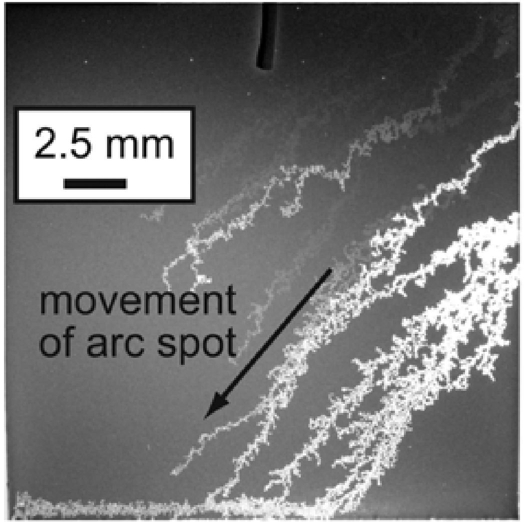


10 ns discharge on Mo in UHV. Photo by B. Jüttner (about 1980).



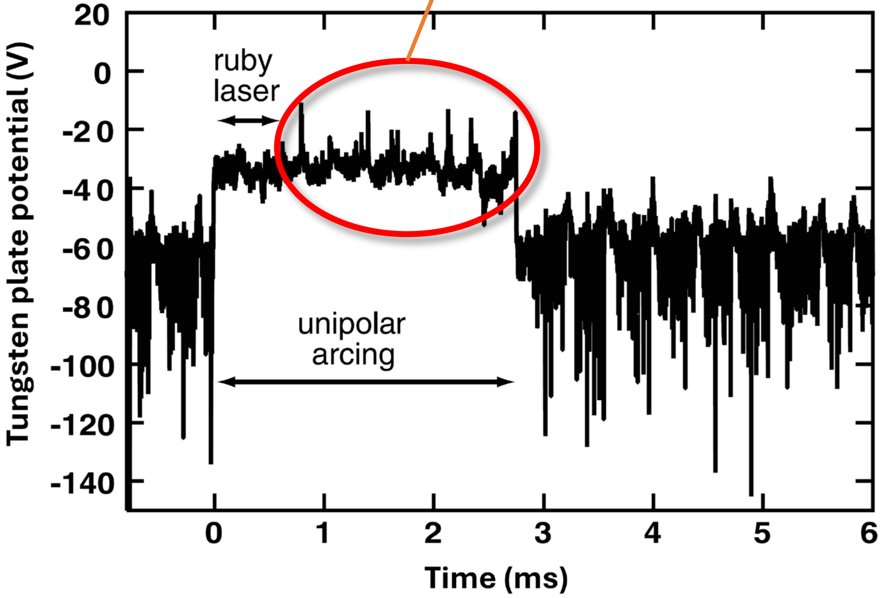
Unipolar arcing (laser triggered)





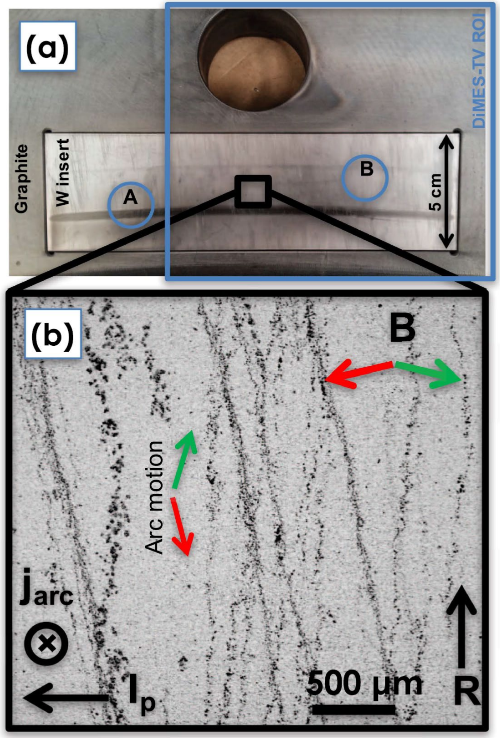
unipolar arcing on
tungsten plate exposed
to helium plasma

arc discharge continues after laser is off!

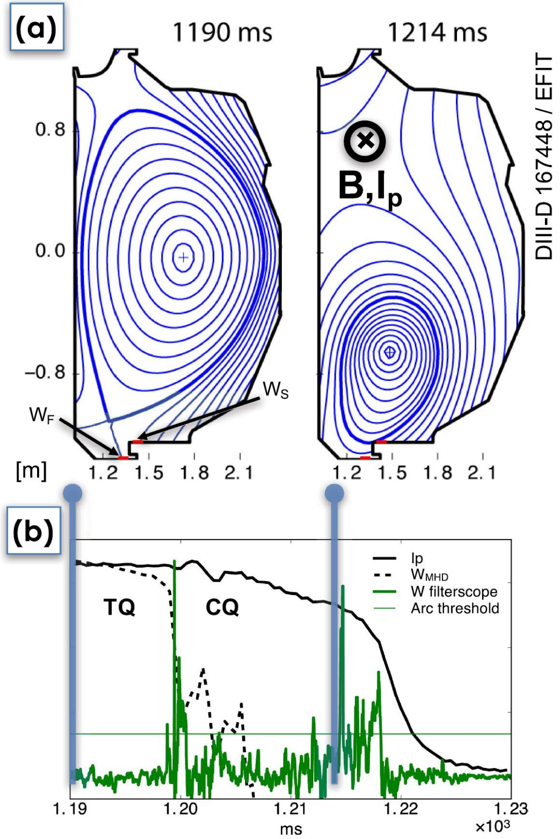


S. Kajita, et al., Nucl. Fusion 49, 032002 (2009).

Unipolar arcing – a big issue in fusion machines



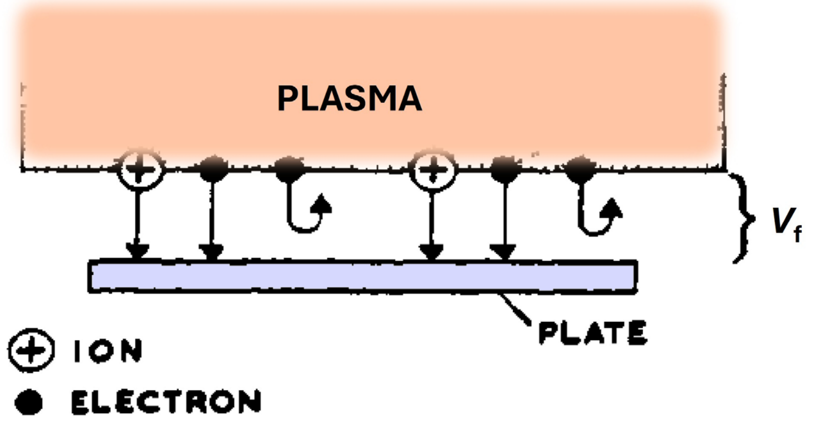
arc traces on tungsten



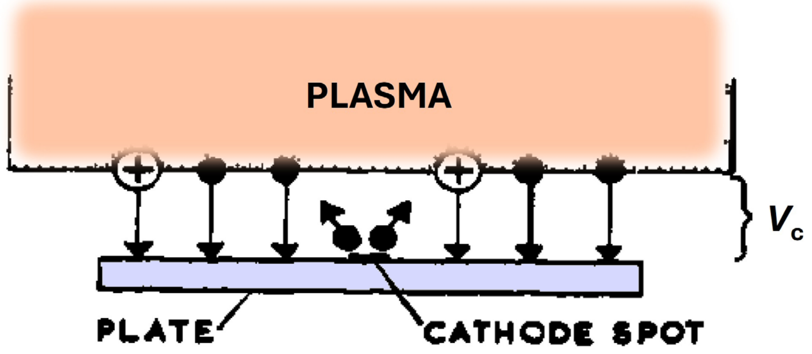
arcing is particularly pronounced during Edge-Localized Modes (ELMs) and disruptions, when the wall is exposed to hot, dense plasma

I. Bykov, et al., Physica Scripta T107, 014034 (2017).

Early models of unipolar arcs: Robson & Thoneman



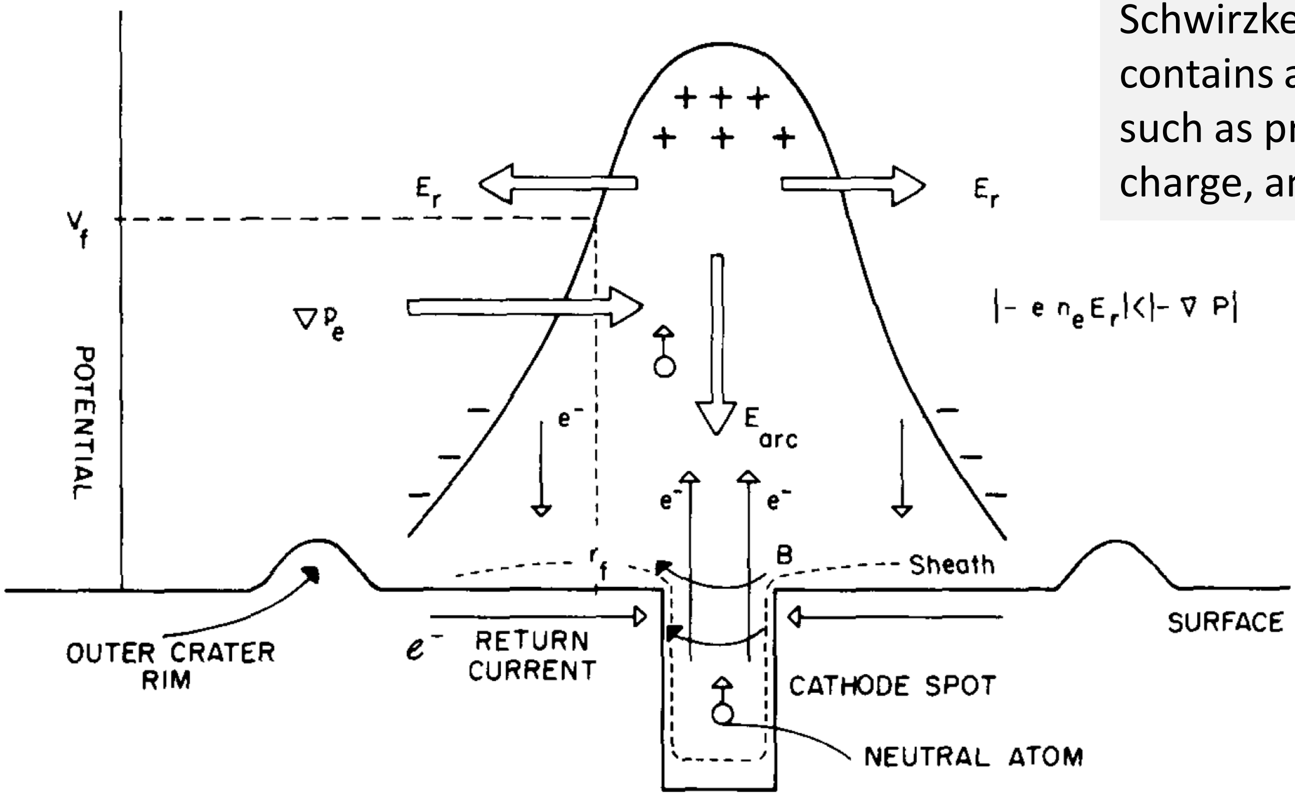
A cathode spot can ignite if $V_{float} > V_c$.
implicitly implying high field conditions on surface as a precondition for unstable electron emission and cathode spot formation



After ignition of cathode spots, the sheath voltage is reduced to the burning voltage V_c of the unipolar arc discharge

A. E. Robson and P. C. Thonemann, Proc. Phys. Soc. 73, 508 (1959).

Early models of breakdown and unipolar arcs



Schwirzke, 1984, 1991
contains already important elements such as pressure gradients, space charge, and resulting electric fields

F. R. Schwirzke, J. Nucl. Mater. 128-129, 609 (1984) and IEEE Trans. Plasma Sci. 19, 690 (1991).

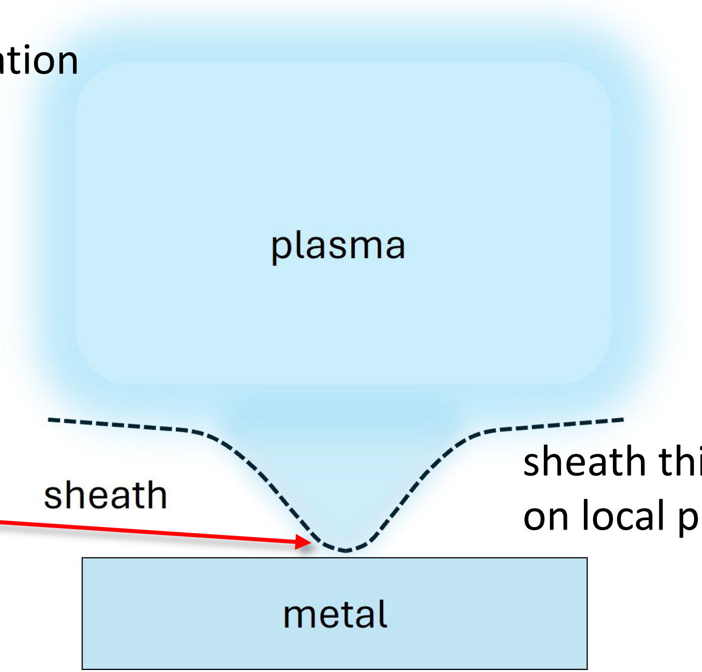
Sheath considerations

sheath calculations are all based on the Poisson equation $\nabla^2\varphi = -\frac{e}{\varepsilon_0}\left(\bar{Q}\, n_i - n_e\right)$

sheath thickness, Child-Langmuir approximation

$$s = \frac{2}{3}\varepsilon_0^{1/2}\left(\frac{2}{e\,kT_e}\right)^{1/4}\frac{V_{\text{sheath}}^{3/4}}{n_i^{1/2}}$$

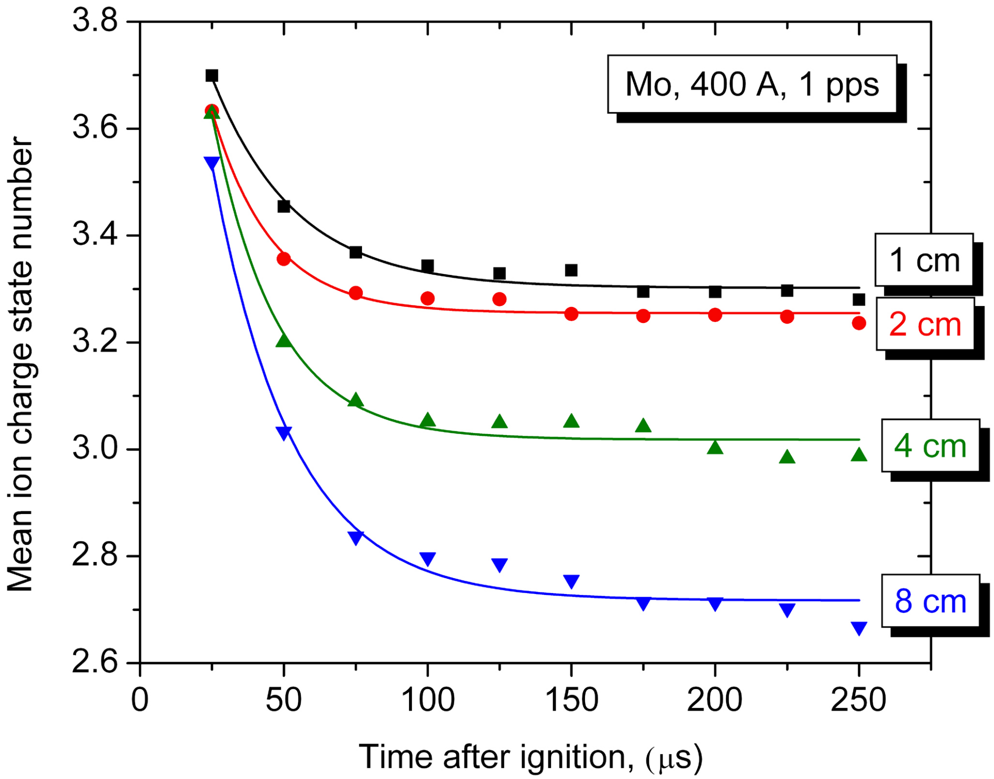
plasma density at cathode is extremely dense
→ thin sheath and high field strength



sheath thickness depends on local plasma density

A. Anders, Phys. Plasmas 33, 063505 (2026).

Ion charge states in the spot vicinity



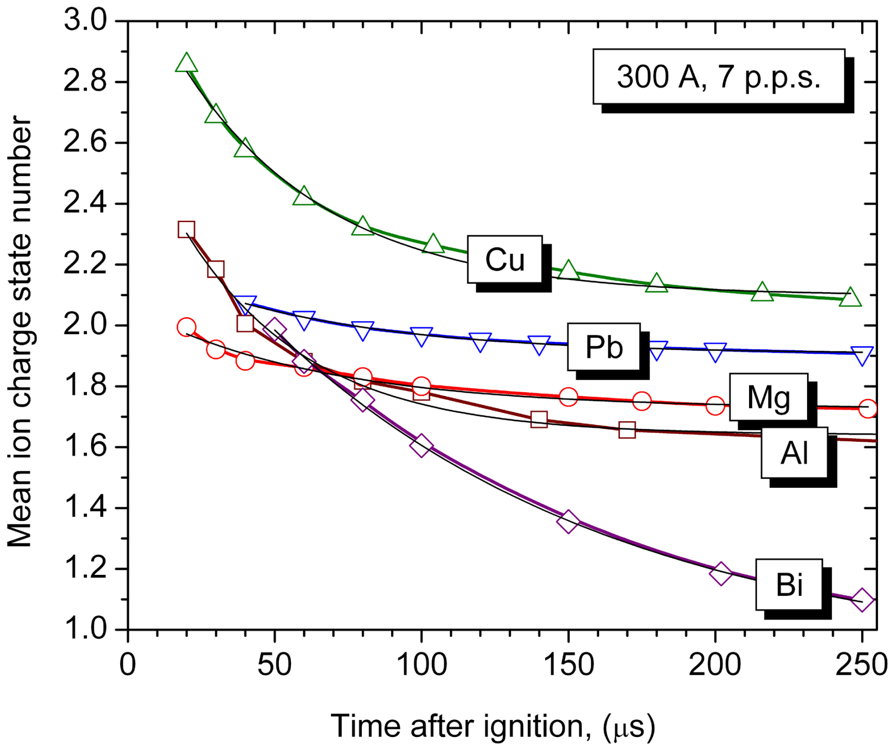
charge exchange collisions reduce higher charge states

→ **charge states at spot are actually higher than we generally think**

→ **and spot plasma is hotter than we generally think**

A. Anders, et al., J. Appl. Phys. 102, 043303 (2007).

Further evidence of charge exchange effects



further evidence: Bismuth has higher vapor pressure than Cu, Pb, Mg, Al → drop of charge states is stronger than other elements

A. Anders, et al., J. Appl. Phys. 102, 043303 (2007).

Current balance for cathodic (vacuum) arcs and unipolar arcs

Since we see a cathode spot, it is intuitive to consider

1. the region of electron emission (spot area) and
2. a ring area around it, where emission from the PFC (plasma facing component) is negligible.

$$I_{spot} = I_{e,\text{spot,from PFC}} - I_{i,\text{spot,from PFC}} = \int_{A_{spot}} \left(j_e + j_i \right) dS$$

$$I_{ring} = I_{i,\text{ring, to PFC}} - I_{e,\text{ring, to PFC}} = \int_{A_{ring}} \left(j_e + j_i \right) dS$$

$$I_{spot} + I_{ring} = \begin{cases} I_{arc} & \text{for vacuum arcs} \\ 0 & \text{for unipolar arcs} \end{cases}$$

A closer look at ion and electron currents

One may distinguish the type (or origin) of ions, to emphasize the role of ions from the expanding spot plasma,

and

write down an expression for the electron return current

$$I_{i,\text{ring, to PFC}} = I_{i,\text{ring, spot plasma to PFC}} + I_{i,\text{ring, background to PFC}}$$

$$I_{\text{e,ring, to PFC}} = I_{\text{e,ring, spot plasma to PFC}} + I_{\text{e,ring, background to PFC}}$$

Of special interest – to explain unipolar arcs – is the electron return current

integrating the electron current density to a PFC over the ring area from r_1 to r_2

$$I_{e,\text{ring, to PFC}} = \int_{A_{ring}} j_e \, dS = -e\left(\frac{k_B}{2\pi m_e}\right)^{1/2} \int_{r_1}^{r_2} n_e(r)\, T_e^{1/2}(r) \exp\left(-\frac{eV_{sheath}(r)}{k_B T_e(r)}\right) \pi r dr$$

and using the plasma expansion formula from a point-like source $n_e(r) = C\dfrac{I_{arc}}{(r+r_1)^2}$

and neglecting electron temperature changes, we get an expression that we can use for estimating the electron return current:

$$I_{e,\text{ring, spot plasma to PFC}} = -C\, I_{arc}\, e\left(\frac{\pi k_B T_e}{2m_e}\right)^{1/2} \exp\left(-\frac{eV_{sheath}}{k_B T_e}\right) \ln\left(\frac{r_2}{r_1}\right)$$

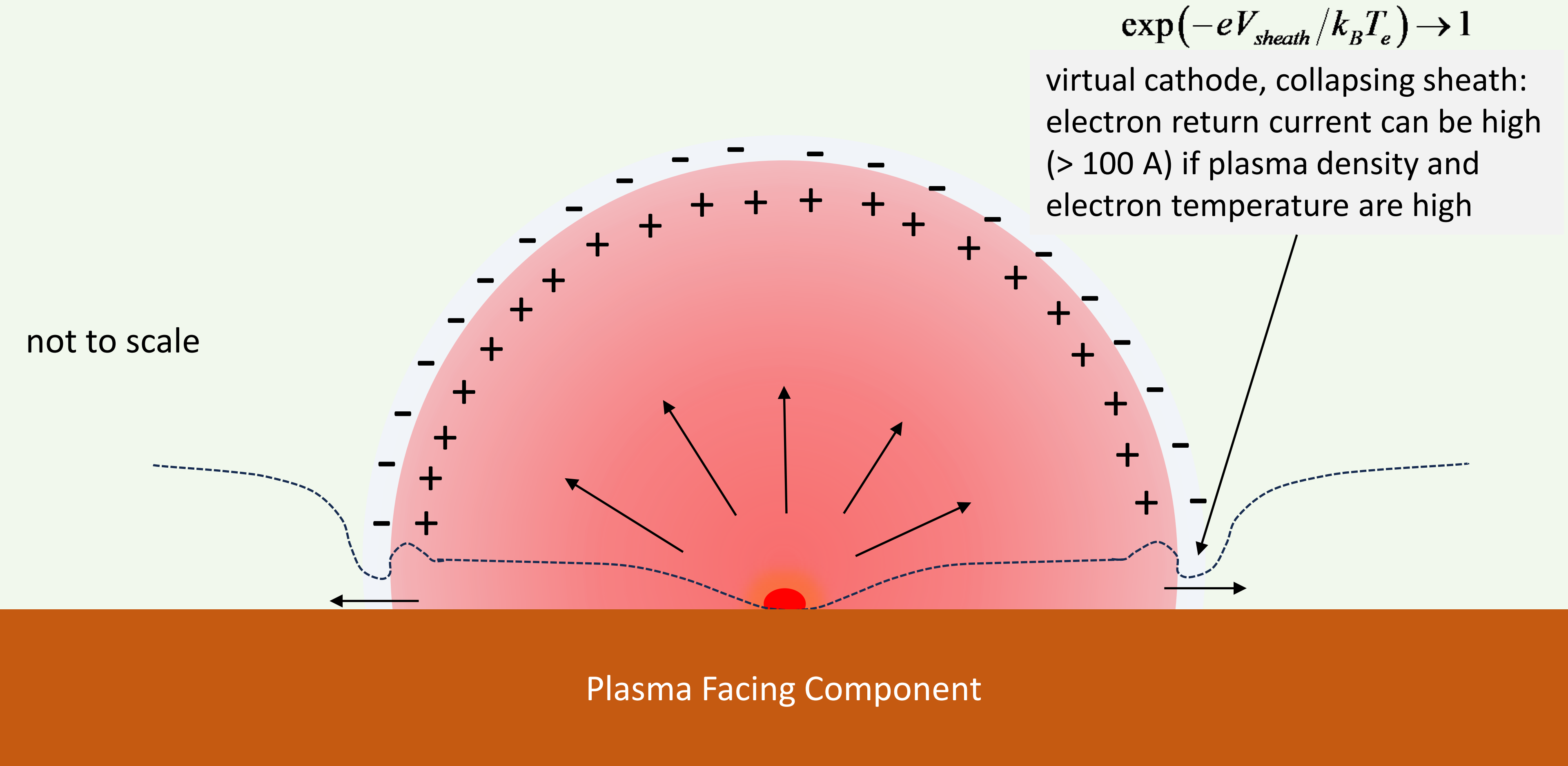
the sheath potential can be locally changed by the traveling double layer of expanding plasma

Analogously, we can get an expression for the ion return current

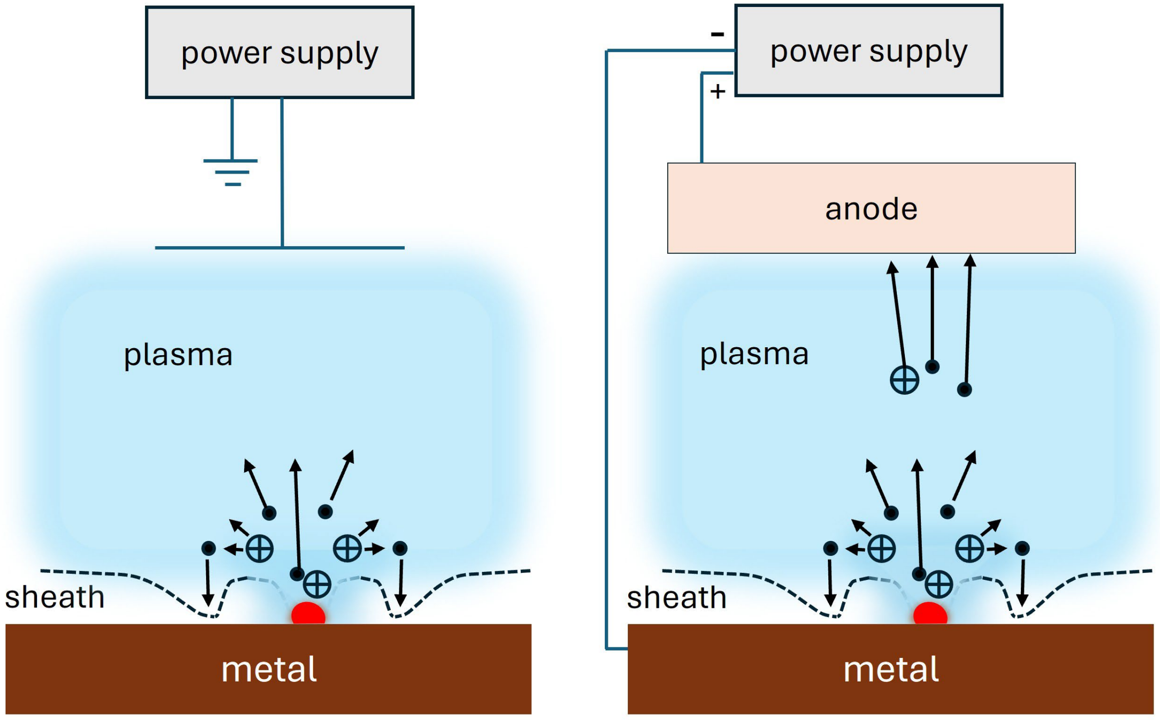
$$I_{i,\text{ring, spot plasma to PFC}} = e\pi\, C\, I_{arc}\left(\frac{k_B T_e}{m_i}\right)^{1/2} \ln\left(\frac{r_2}{r_1}\right)$$

A. Anders, Phys. Plasmas 33, 063505 (2026).

Traveling double layer of an expanding plasma



Graphic presentation of current balance



unipolar arc *vacuum arc*

Consequences

→ current in spot is higher than arc net current

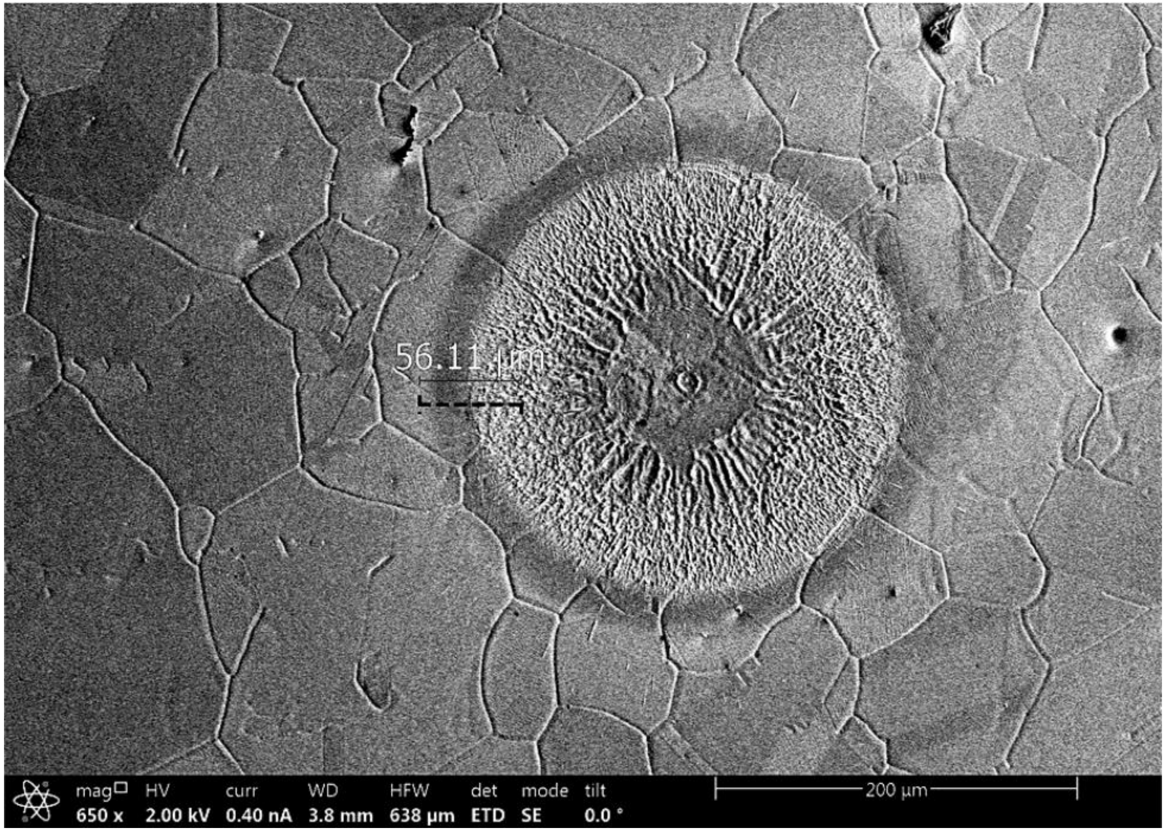
→ vacuum arc has two cathodes:

1. the anode connected to the arc power supply
2. the ring region around the cathode spot

The transient double layer formation is compatible with ion acceleration and transient nature of spot parameters.

A. Anders, Phys. Plasmas 33, 063505 (2026).

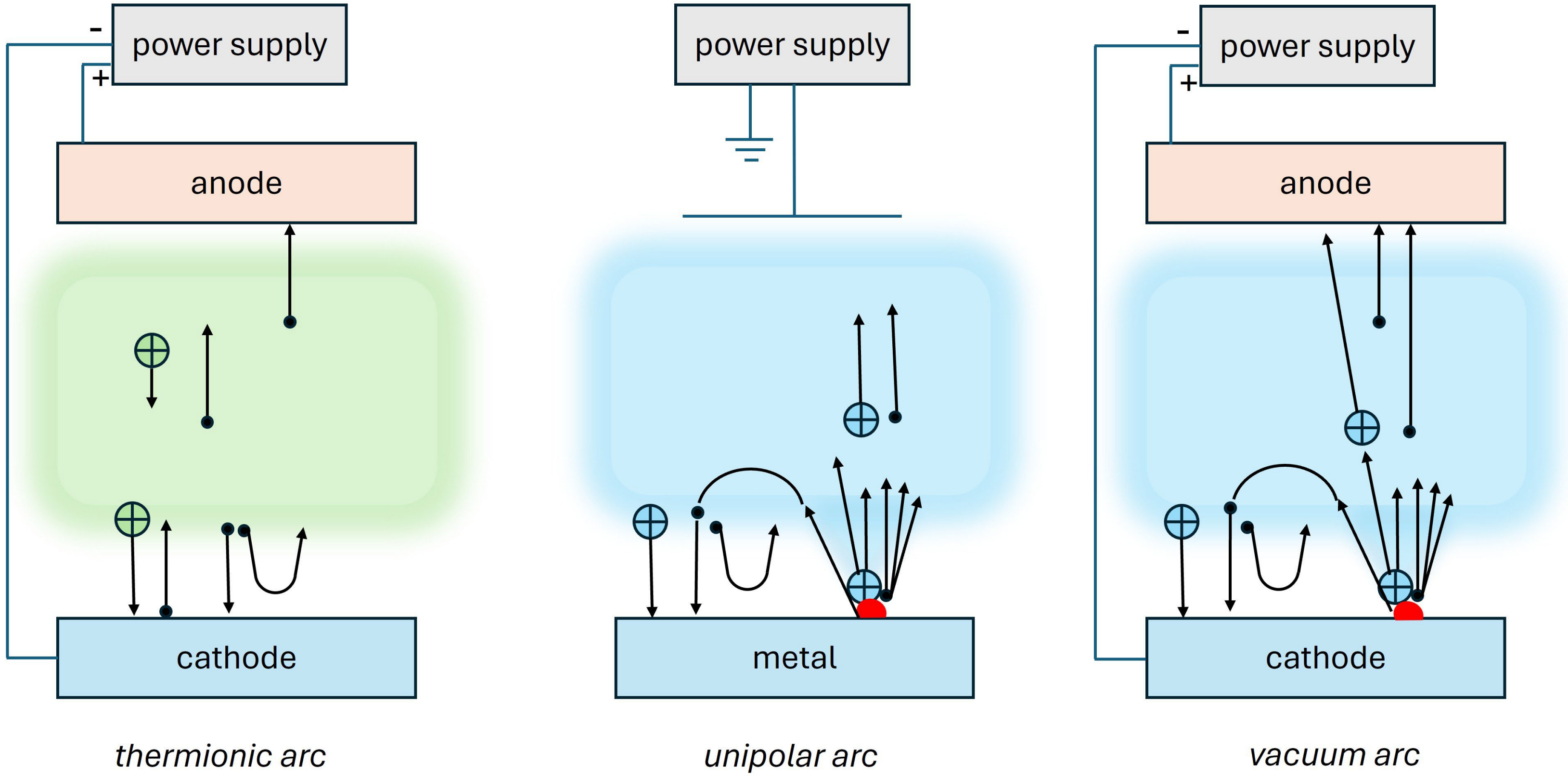
Is there any evidence of a ring area around the spot?



Surface damage on a cryogenically conditioned electrode after vacuum breakdown, showing a large, ringlike area modified by the breakdown event

Y. Ashkenazy, in 12th Int. Workshop on Mechanisms of Vacuum Arcs (MeVArc 2025) (Uppsala, Sweden, 2025).

Current balances of arcs

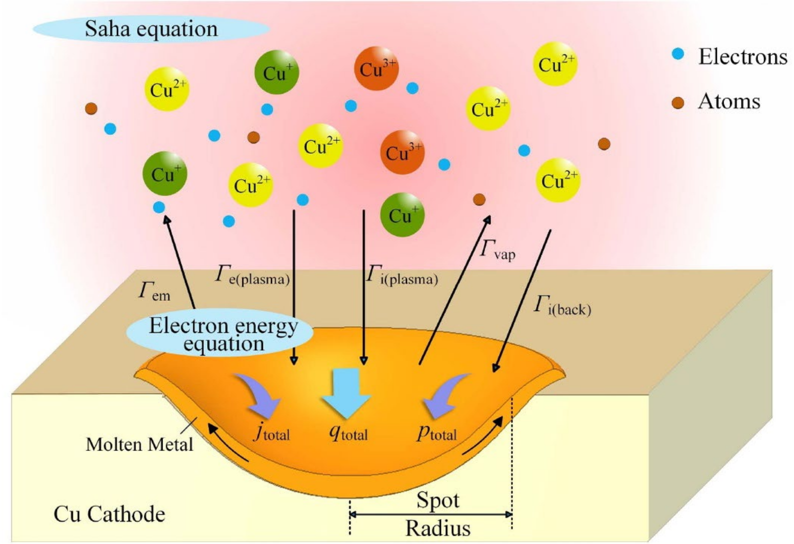


A. Anders, Phys. Plasmas 33, 063505 (2026).

Why is the concept different than traditional models?

Most traditional models…

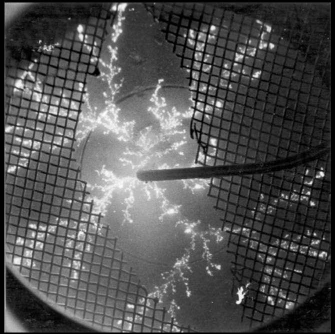
- do not account for ions moving *away* from the cathode, i.e. the need to compensate their current by electron current
- neglect the electron return current *outside* the spot area because they neglect the effect of the double layer formed by the pulsed, expanding plasma on the local sheath properties
- neglect the dynamics of the pulsed nature of the plasma gradient
- hence fail to unify vacuum arcs and unipolar arcs.

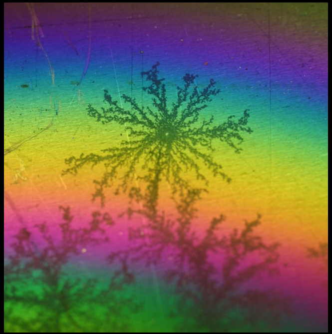


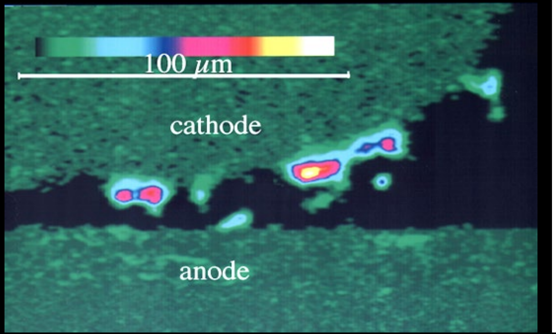
X. Liu, J. Phys. D: Appl. Phys. 59, 285205 (2026).

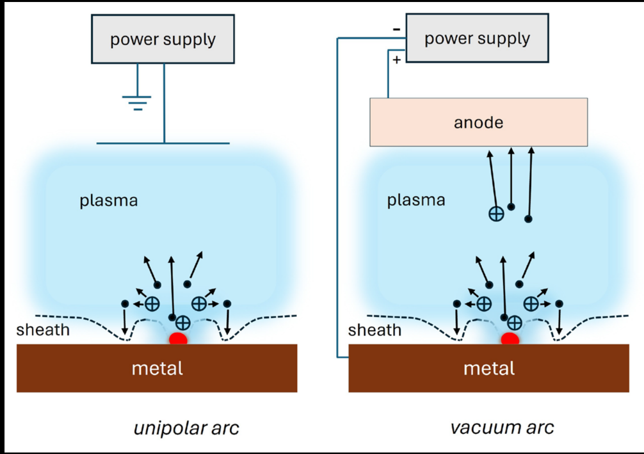
Traditional models may be applicable to the post-explosion stage of a spot. The here-presented concept is a blueprint for time-dependent modeling including the ring area around the spot. The quest is not completed.

Summary and Conclusions









1. vacuum arcs and unipolar arcs are similar, both have nonstationary cathode spots
2. breakdown and ignition of spots are driven by high electric field strength
3. plasma expansion is governed by pressure gradients, which cause an expanding, traveling double layer
4. unipolar arcs have net zero current → expanding area around a spot is anode, enabled by double layer
5. vacuum arc electron current > net current since ions move in the "electrically wrong" direction
6. given the similarity, vacuum arcs have two anodes: the ring around each spot and the "powered anode"
7. the electron emission in vacuum arc cathode spots is even higher than we usually assume
8. this approach is a blueprint for simulations, consistent with the non-stationary nature of cathode spots

A. Anders, Phys. Plasmas 33, 063505 (2026).

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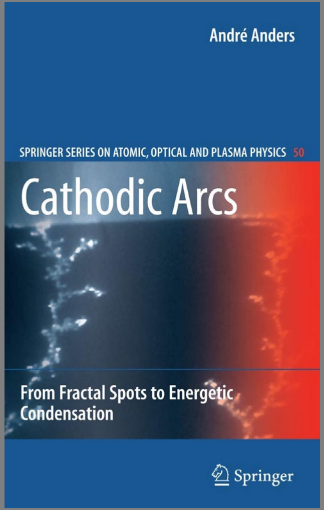

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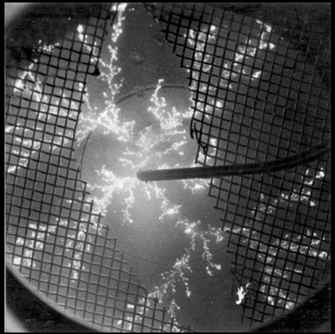
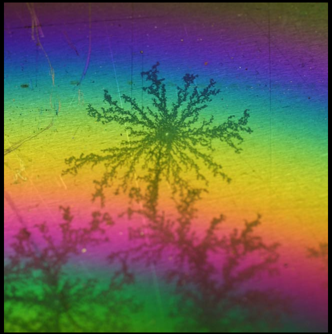
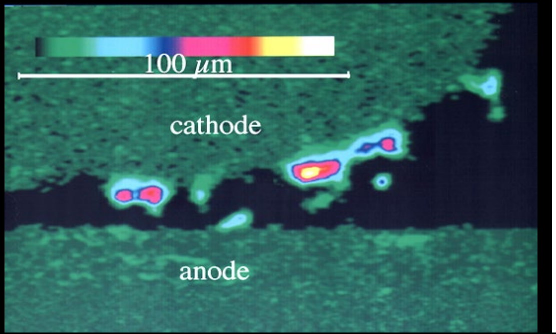
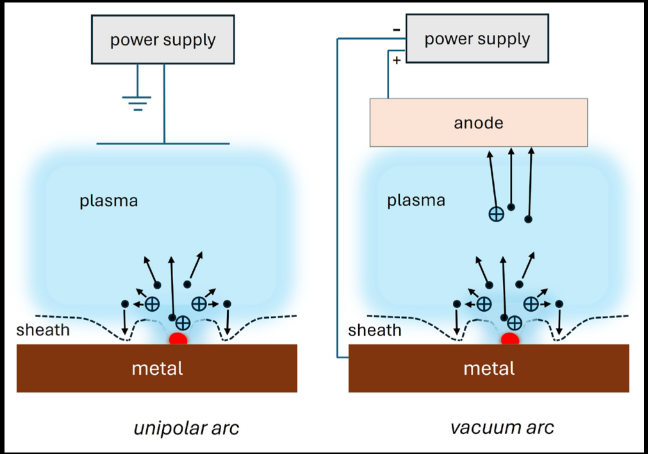
Summary and Conclusions

Q&A









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